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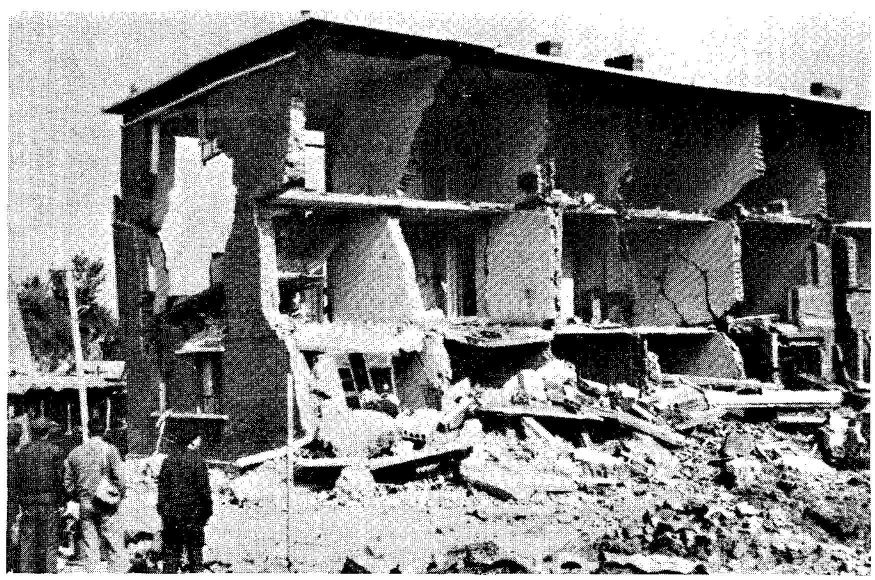
THE 1976 TANGSHAN, CHINA EARTHQUAKE



Papers Presented at the
2nd U.S. National Conference
on Earthquake Engineering
Held at Stanford University
August 22-24, 1979

March 1980

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Introduction
by
James M. Gere and Haresh C. Shah

March 1980

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16. Abstract (Limit: 200 words)

Papers presented in this proceedings contain descriptions of the damage done by the Tangshan earthquake, give some of the lessons learned from the quake, explain measures being taken to mitigate such disasters in the future, and discuss various technical aspects of earthquake engineering. Isoseismal maps for the earthquake are included. Strong-motion records obtained during the earthquake are described and seismological data are given. Titles of the papers presented include: Experience in Engineering from Earthquake in Tangshan and Urban Control of Earthquake Disaster; Some Engineering Features of the 1976 Tangshan Earthquake; Field Phenomena in Meizoseismal Area of the 1976 Tangshan Earthquake; Earthquake Damage to Pipelines; Damage in Tianjin During Tangshan Earthquake; and Empirical Criteria of Sand Liquefaction.

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The visit of the Chinese Delegation was made possible by the cooperation of LI JINGZHAO, Vice Minister, State Capitol Construction Commission, Beijing, China, LIU HUIXIAN, Professor and Director of the Institute of Engineering Mechanics, Chinese Academy of Science, Harbin, China, and XU ZHAOXIANG, Counselor for Science and Technology at the Embassy of the People's Republic of China, Washington, D. C. As the Co-Chairmen of the U.S. National Conference, we would like to express our appreciation to them for arranging this visit.

Most important of all, we wish to thank the Delegates for attending this Conference and presenting their papers. Not only has the engineering profession benefited from the dialogue made possible by their visit, but we personally have made new friends in China. For this opportunity we are very grateful, and we look forward to future contacts not only with them but also with other engineers in China.

We are indebted to the Earthquake Engineering Research Institute and especially to Dr. John A. Blume, President, for sponsoring the visit of the Chinese delegates and for arranging to have this report published.

The National Science Foundation contributed financially toward the publication of this report, and this support is gratefully acknowledged.

PREFACE

The papers appearing in this report were presented at the 2nd U.S. National Conference on Earthquake Engineering held at Stanford University, August 22-24, 1979 and sponsored by EERI. They contain descriptions of the damage done by the Tangshan earthquake, give some of the lessons learned from the quake, explain measures being taken to mitigate such disasters in the future, and discuss various technical aspects of earthquake engineering. Isoseismal maps for the earthquake appear on pages 12, 33, 47, and 70. Strong-motion records obtained during the earthquake are described on page 42. Also, seismological data are given on pages 11, 33 and 45.

The papers were written and presented by members of the delegation from the People's Republic of China who came to the U.S. to attend this Conference. The delegation was invited to the Conference by Dr. John A. Blume, President of EERI, who supervised the arrangements for their stay in the U.S. Financial support for their visit was provided by the National Science Foundation. The delegates spent one week at Stanford, living in a residence hall and attending the Conference. During their stay at Stanford they also visited the U.S. Geological Survey in Menlo Park and other nearby places. After the Conference they traveled to San Francisco, Berkeley, Los Angeles, Pasadena, Urbana, New York City, Cambridge and Washington, D.C. On this journey they visited the campuses of the University of California (Berkeley), University of California (Los Angeles), University of Southern California, California Institute of Technology, University of Illinois, Columbia University, Massachusetts Institute of Technology, and Harvard University. In addition, they visited many engineers and others at their places of business.

Delegates to the 2nd U.S. National Conference on Earthquake Engineering from the People's Republic of China

Front row, left to right: Professor Haresh C. Shah of Stanford University, Nie Fenglan, Li Jingzhao, Ye Yaoxian, Xie Junfei, Gong Yongsong.
Back row, left to right: Jin Guoliang, Yu Li, Chen Dasheng, Sun Shaoping, Liu Xihui.

The group was known officially as the China Urban Earthquake Disaster Control Technique Delegation. The delegates were as follows:

LI JINGZHAO, Head of the Delegation; Vice Minister, State Capitol Construction Commission

YE YAOXIAN, Deputy Head of the Delegation; Vice Chairman, Earthquake Engineering Committee, Architectural Society of China; Leading Member, Office of Earthquake Resistance, State Capitol Construction Commission; Deputy Chief Engineer

XIE JUNFEI, Deputy Director Engineer, Institute of Engineering Mechanics, Chinese Academy of Science; Associate Researcher

CHEN DASHENG, Deputy Director Engineer, Institute of Engineering Mechanics, Chinese Academy of Science; Assistant Researcher

SUN SHAOPING, Leading Member, Municipal Engineering Institute of Beijing; Engineer

JIN GUOLIANG, Deputy Director, Earthquake Engineering Institute of Tianjin; Engineer

GONG YONGSONG, Council Member, Earthquake Engineering Committee, Architectural Society of China; Office of Earthquake Resistance, State Capitol Construction Commission; Engineer

LIU XIHUI, Director Engineer, Institute of Structures, Academy of Building Research of China

YU LI, Hongshan Testing Machinery Plant of Tianshui; Engineer

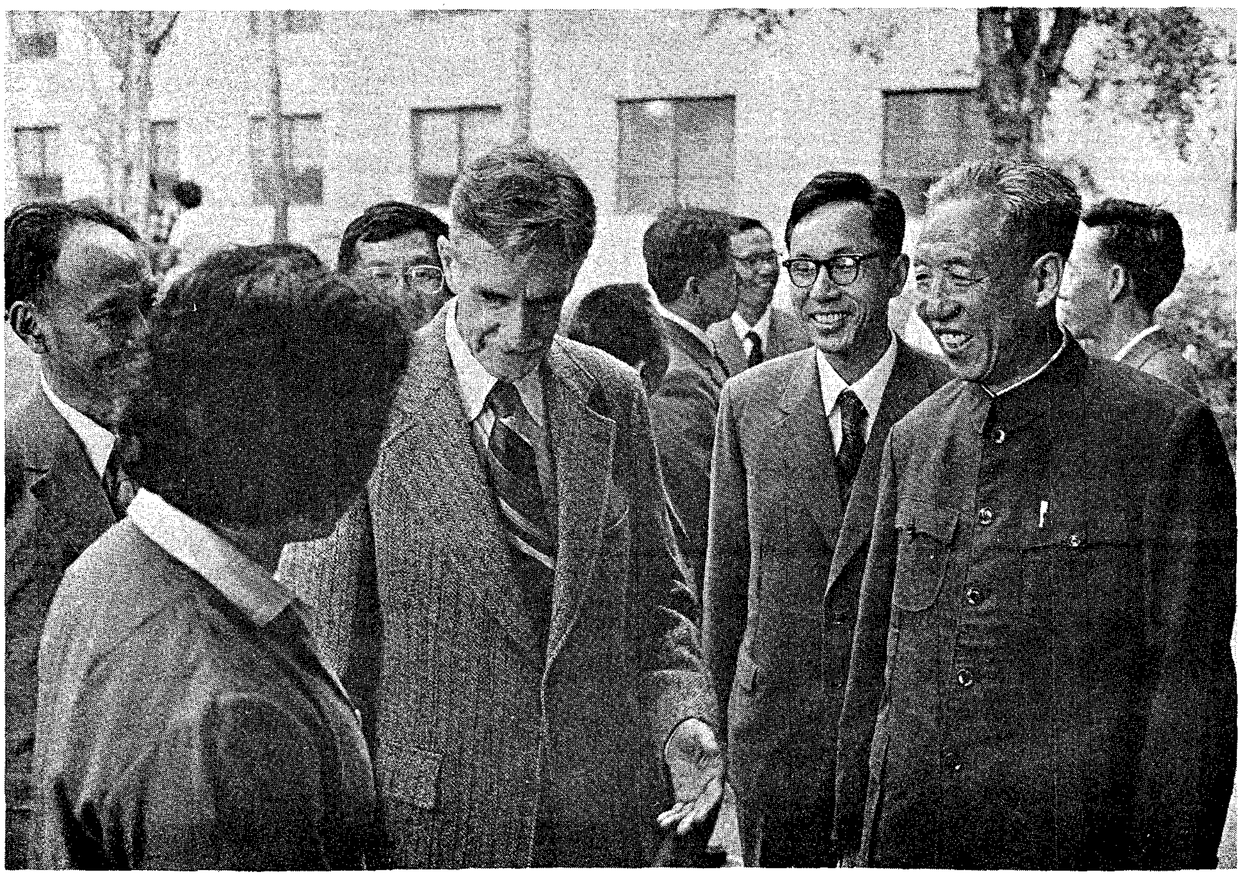
NIE FENGLAN, Academy of Building Research of China; Editor and Interpreter

In addition to the official delegates, two other visitors from China attended the Conference:

C. H. CHANG, Associate Professor, Tsing Hua University, Beijing

HU YUXIAN, Assistant Director, Chinese Academy of Science

Dr. John A. Blume, EERI President, with some of the Chinese delegates



Left to right: Gong Yongsong, Nie Fenglan, C.K. Chen (San Francisco engineer), Dr. Blume, Xie Junfei, Chen Dasheng, Yu Li, Ye Yaoxian, Li Jingzhao, and Liu Xihui.

Message of Congratulations to the
U.S. National Conference on Earthquake Engineering

Respected Mr. Chairmen,
Ladies and Gentlemen,

The China Urban Earthquake Disaster Control Technique Delegation is very happy to have the opportunity of attending the U.S. National Conference on Earthquake Engineering. We warmly congratulate the Conference on its successful convocation and wish it a great success.

As is known to all, there are more than 60 countries in the world which are threatened by earthquakes, 30 or more of them are subjected to more serious threat. China has repeatedly suffered a great deal from earthquakes. Your country has also suffered a lot from earthquake damages. At present, it is a question of great concern to many countries to mitigate earthquake disasters and to safeguard the safety of people's life and property.

In the past decades earthquake engineering, as a new science, has played an important role in mitigating earthquake disaster and has obtained satisfactory results. In your "Ten-Year Plan of Research on Earthquake Prediction and Earthquake Engineering" made in 1965, you mentioned that no matter whether earthquakes can be predicted or not the main contribution of science and technology to the earthquake problem lies in the field of engineering. Such presumption stands to reason. Many strong earthquakes in the world have shown that the development of earthquake engineering and improvement of aseismic design of buildings are important means for earthquake disaster mitigation. Therefore, the work of scientists and engineers in the field of earthquake engineering is of great importance to mankind. We believe that with the advance of science and technology, the perfection of means of prediction, and the development of engineering, the day will come when earthquakes can be conquered by man. In this field, we Chinese scientists and engineers would like to exchange experiences and cooperate closely with our colleagues from the United States and other countries. Let us make joint efforts for the early fulfillment of this fond hope of ours.

We wish the Conference a great success.
We wish Mr. Chairmen and Ladies and Gentlemen
the best of health.

(The preceding Message was delivered by Li Jingzhao, Head of the Delegation, on August 22, 1979)

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INTRODUCTION

by

James M. Gere and Haresh C. Shah

The Earthquake

The 1976 Tangshan earthquake was one of the great disasters of history. On July 28, 1976 in the early morning (3:42 a.m., local time) this major earthquake occurred in a highly seismic area of northern China. The epicenter was located directly under the city of Tangshan, an important industrial and coal mining center, located 100 miles east of Beijing (Peking). About one million people lived in Tangshan and about two million lived within 25 miles of the epicenter.

Nearly 100 percent of the living quarters in Tangshan were destroyed, as were about 80 percent of the industrial buildings. The damage included collapsed bridges, bent railroad tracks, overturned trains, damaged highways, toppled chimneys (over 10,000 large industrial chimneys fell), broken pipelines, and cracking of dams, although no severe flooding occurred. About 240,000 people were killed in the earthquake and about 164,000 were seriously injured, according to figures released by the Chinese in November 1979.

Industrial losses were especially great because Tangshan is a center for coal mining, iron and steel production, and the manufacture of cement. It is also a major railway center, and there were 28 trains passing through at the time of the quake. Seven of these trains were actually overturned, others were damaged and derailed. About 30,000 coal miners on the night shift were working underground when the earthquake occurred. All of them eventually returned safely to the surface, although much damage was done to the mines.

Ground breakage at the surface near Tangshan was about 1.5 meters horizontally and 0.8 meters vertically. Ground motion records showed relatively large vertical accelerations.

Tangshan is located about 40 miles from the seacoast at Bohai Bay, and liquefaction and subsidence of the land were widespread in the coastal areas. Land settlement was as much as 10 feet, resulting in settling, tilting, and falling of buildings and bridges. One coastal village was inundated by the sea due to subsidence.

The main earthquake had a magnitude of 7.8 and a focal depth of 12 to 16 kilometers. It was felt for at least 500 miles in all directions. In Tianjin, the provincial capital about 70 miles southwest of Tangshan, as well as in Beijing and many other cities, millions of people immediately evacuated their buildings and moved outdoors to be safe from the effects of aftershocks. American tourists who were moved out of their hotels reported that the Chinese were well prepared for evacuation and that everyone moved quietly and promptly.

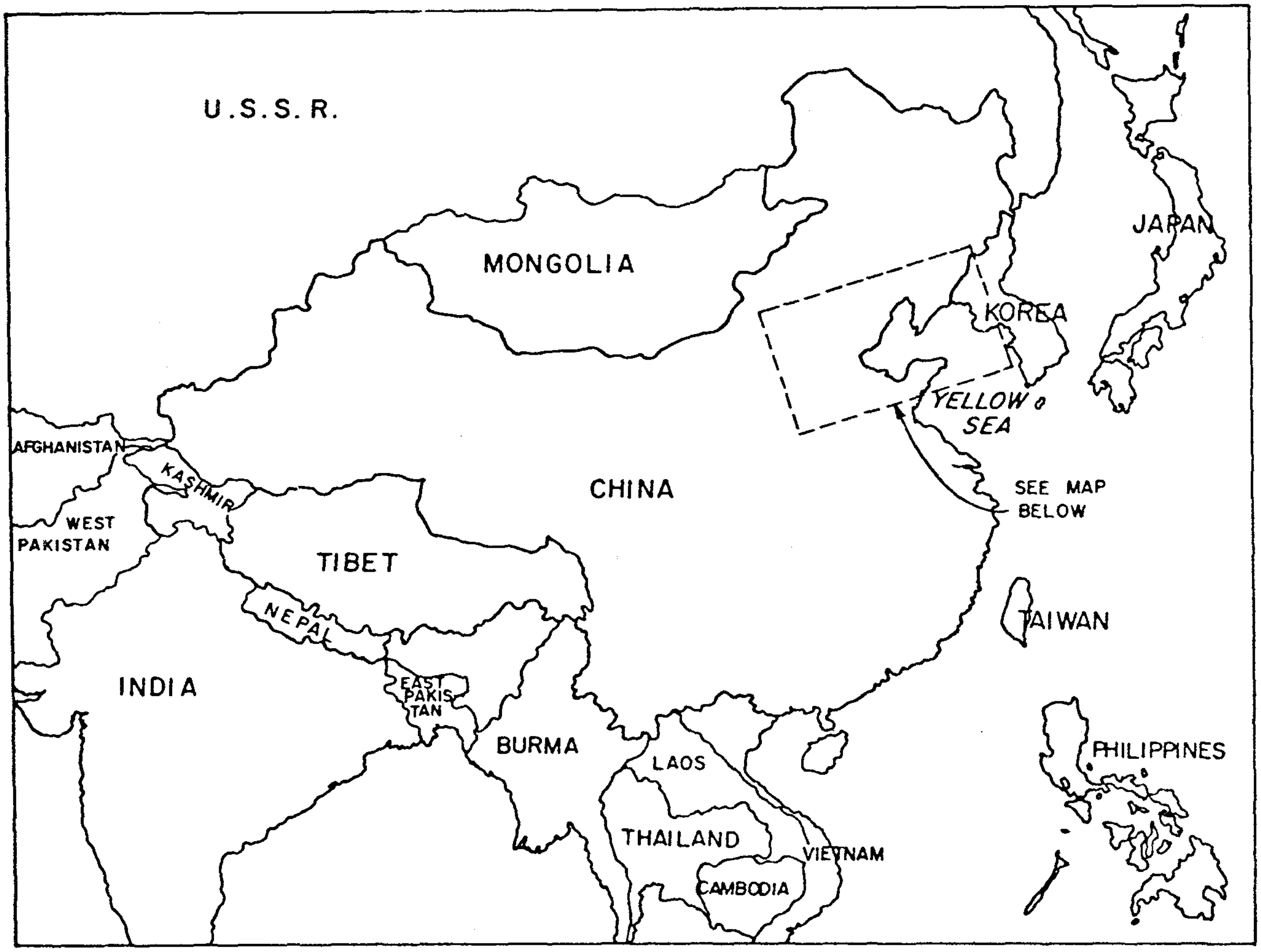
A major aftershock occurred at 6:45 p.m. the same day. It had a magnitude of 7.1 and was centered only a few miles from the main early-morning quake. In Tangshan this second earthquake destroyed most of what survived the first one. The Luanho River bridge, which was 800 meters long, was still usable after the main earthquake but the spans fell into the river during the second quake. There were thousands of other aftershocks, including seven of magnitude 6 or greater. Later in the same year (November 15, 1976), a magnitude 6.9 earthquake struck the city of Ningho, only 30 miles south of Tangshan, resulting in much additional damage.

China is part of the Eurasian plate which is being squeezed from the east by the Pacific and Philippine plates and from the south by the Australian plate. All three of these plates are being subducted under the Eurasian plate. The subduction zone for the Philippine plate includes the deep ocean trench along the Ryuku Islands between Taiwan and Japan, and for the Pacific plate includes the Japan and Kurile trenches. The Australian plate is being subducted at the Java trench and along the Himalayas, and the latter action is responsible for the uplifting not only of the Himalayas but also the entire Tibetan plateau. The pressure from these adjoining plates probably accounts for the high level of seismicity in China. The region around Tangshan has been known as an area of high seismic activity for hundreds of years, as shown by Chinese earthquake records that go back over 2,500 years. In 1966 there were three large earthquakes in Hebei Province south of Beijing, in 1967 a magnitude 6.3 quake occurred in the same general area, and in 1969 there was a 7.4 magnitude earthquake in the vicinity of Bohai Bay.

About a year and a half before the Tangshan earthquake some remarkable events occurred in Liaoning Province. In this province is the city of Haicheng, about 250 miles east of Tangshan. The area around Haicheng had been studied carefully by seismologists for some time. They had noted a number of unusual phenomena, including changes in geomagnetism and the occurrence of what they believed to be foreshocks of an impending large earthquake. Hence, on February 4, 1975 the area around Haicheng was put on the alert, some people were evacuated, emergency duties were assigned, and disaster relief facilities were mobilized. An earthquake of magnitude 7.3 occurred at 7:36 pm that day, only a few hours after the emergency measures were instituted. Although much damage to buildings took place, there were relatively few casualities. It is estimated that thousands of lives were saved by the precautionary measures.

Similar studies had been going on in the Tangshan and Beijing areas, especially since 1970. In 1974 earthquake warnings were issued and some evacuations took place, but no earthquake occurred. Seismologists noted continuing changes taking place in that area, especially uplifting of the land, changes in radon content, and changes in geomagnetism. Long-range predictions were issued in early 1976, and the populace was warned by radio to prepare for an earthquake. However, the evidence was not conclusive enough to result in any short-range predictions before the July 28 quake.

Most structures in Tangshan had not been designed to resist earthquakes. Many were built of unreinforced brick and collapsed during the shaking. Rebuilding of the city and its environs has been taking place under newly developed seismic codes and a new city plan. The plan includes a core city of about half a million people surrounded by open areas and additional satellite cities of 100,000 to 300,000 population. The industrial part of the city has already been rebuilt. The Chinese government has advised people in rural areas to strengthen their homes with bamboo reinforcement, a method which has proven to be practical.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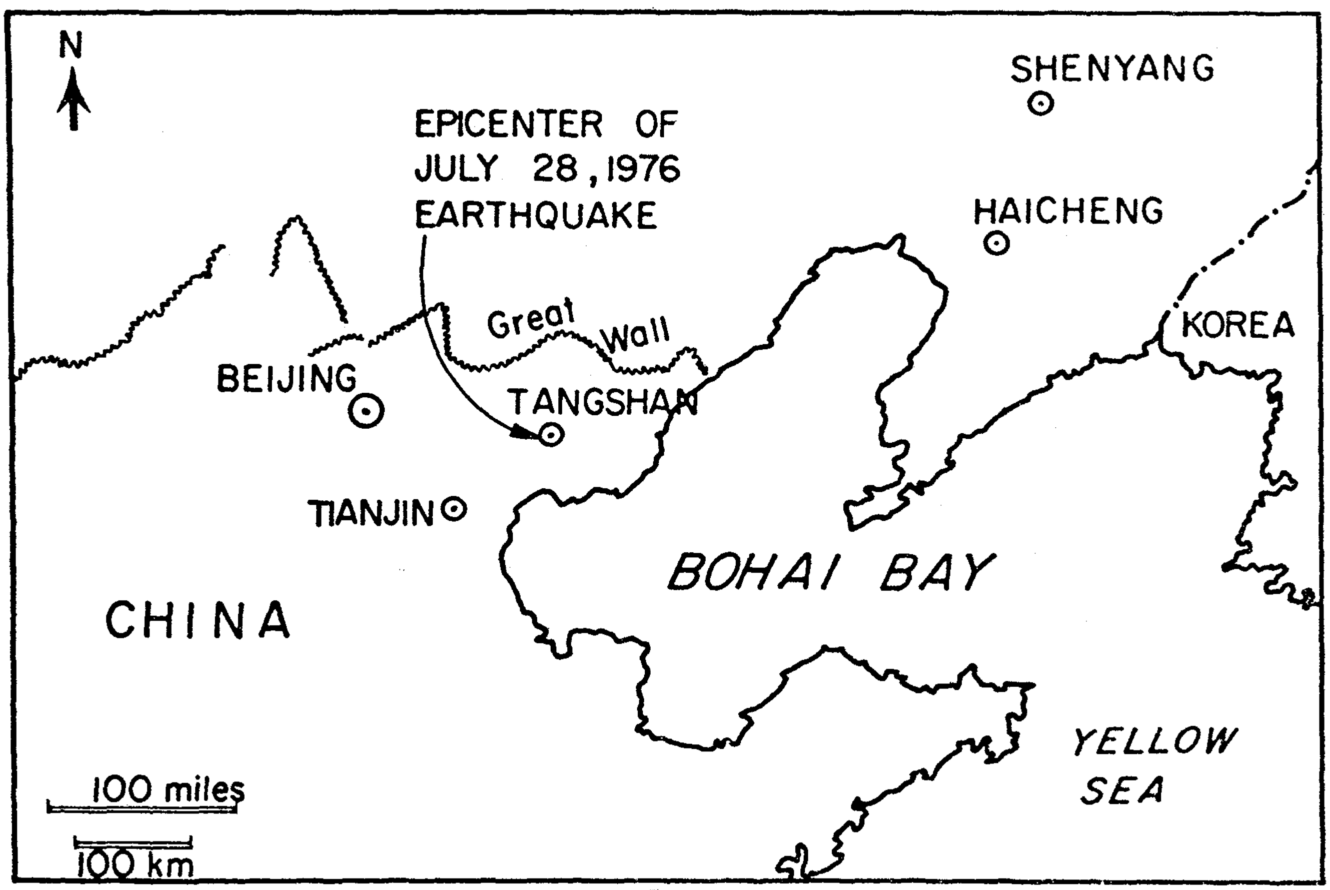
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EPICENTER OF JULY 28, 1976 EARTHQUAKE
HAICHENG
KOREA
Great Wall
BEIJING
TANGSHAN
TIANJIN
BOHAI BAY
CHINA
YELLOW SEA
100 miles
100 km

Lessons Learned and Relearned

1. China has a lengthy record of past earthquakes and has put a great effort into methods of predicting earthquakes. Nevertheless, great earthquakes still occur without warning and cause major damage. It is obvious that success in earthquake prediction in one location is no assurance of success in another location. Efforts directed toward better earthquake predictions must be continued throughout the world, because many lives could be saved by evacuating people from potentially unsafe areas.

2. Buildings that are not designed to resist lateral forces will perform badly in an earthquake. The lack of adequate seismic resistance in most structures was responsible for the great amount of damage. The introduction of seismic provisions in building codes and in engineering design practice is essential for the reduction of damage, injury, and life loss. Codes should recognize adequately the intensities that may be expected in the region and should take into account the importance of the structure.

3. Aftershocks can produce additional damage to structures and can cause the collapse of already-weakened buildings. Structures that have been weakened by an earthquake should be evacuated until they have been repaired and strengthened.

4. The seismic hazards for populated areas must be adequately recognized and seismic zoning must be done properly by knowledgeable engineers. The epicenter of the Tangshan earthquake was located in the densely inhabited part of the city, and the intensity of the earthquake was greater than had been thought probable.

5. Good city planning is needed to reduce the problems of evacuating people and caring for the injured. Narrow streets quickly become jammed and make travel slow and hazardous.

6. A trained populace helps qreatly to reduce panic and needless injury. Earthquake drills and educational programs that inform the public about what to do during and after an earthquake are very valuable.

7. Lifelines such as water supply systems, power lines, communications, and transportation routes must be constructed with earthquakes in mind. Otherwise, nearly complete paralysis of a community can be caused. In Tangshan the supply of water was cut off by damage to pumps and the collapse of numerous water supply structures. The Chinese engineers suggest the following measures for prevention: design water supply structures to resist earthquakes; provide separate water sources for different parts of the city; use networks of pipelines to provide redundancy when breaks occur; and use flexible joints between pipes.

8. Bridges must be carefully designed against earthquakes to prevent collapses. For example, girders should be prevented from falling by some type of tie or stopper. The loss of a bridge crossing a river can create severe difficulties.

9. Unreinforced brick and masonry buildings suffer great damage in earthquakes and should not be permitted in seismic zones. Such structures were responsible for considerable loss of life in the Tangshan earthquake.

10. Buildings with good structural joints tend to hold together in an earthquake. The importance of tieing the parts of the structure together was clearly evident in the damage studies at Tangshan. Weak connections and inadequate bracing contributed to many collapses. Reinforced concrete structures often suffered damage at joints.

11. Strengthening and upgrading of existing structures is both feasible and extremely desirable. Numerous buildings that had been strengthened prior to the earthquake performed well. Methods used included the cementing of reinforcing members to walls and the addition of properly reinforced brick walls.

12. Foundation conditions have a great effect on the extent of damage. Buildings on firm sites (including bedrock) generally fare much better than those located on thick deposits of loose soil. Liquefaction can be a major problem and can result in the settling and tilting of foundations.

13. Chimneys are particularly vulnerable to earthquakes. Proper design, such as the use of vertical and circumferential steel reinforcement, is necessary.

14. Additional research in earthquake engineering is needed in order to guide designers and builders. Effects that are not well understood, such as those due to overturning and large vertical ground motions, caused damage to structures in the Tangshan earthquake. Important earthquakes such as this one should be carefully studied so that knowledge can be improved.

Experience in Engineering from Earthquake in Tangshan and Urban Control of Earthquake Disaster

Ye Yaoxian 1) Liu Xihui 2)

Synopsis

The severe disaster of Tangshan earthquake ranked it among the most serious ones which have ever been recorded in history. In this paper the catastrophe and its causes are outlined. Emphasis will be laid on damages on buildings, life lines and equipments as well as aseismic experience, secondary disasters and related problems in urban planning. Developments in repairing and strengthening of existing buildings, aseismic design and research work after 1976 shock in our country will also be included.

Foreword

More than 230 strong earthquakes with magnitudes above 6 have occurred after the founding of new China. 8 destructive shocks took place in main land (See Table 1), 6 of which occurred in countryside. The earthquake

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1) Deputy Chief Engineer, Leading Member of office of Earthquake Resistance, State Capital Construction Commission.

2). Director Engineer, Institute of Structure, Chinese Academy of Building Research.

Recent Destructive Earthquake in China

Table 1

No	Time of Occurrence		Location of Epicenter		Magnitude	Peak Intensity
	Date	Time	Instrumental Epicenter	Macro-epicenter		
1	Mar.8, 1966	05-29	37°21'N 114°55'E	Xingtai Hebei	6.8	9
	Mar.22,1966	16-11	37°30'N 115°05'E		6.7	9
	Mar.22,1966	16-19	37°32'N 115°03'E		7.2	10
2	Jan.5, 1970	01-00	24°12'N 102°41'E	Near Tonghai Yunnan	7.7	10
3	Feb.6, 1973	18-37	31°30'N 100°24'E	Near Luhuo	7.9	9-10
4	May 11,1974	03-25	28°12'N 104°06'E	Near Daguan Yunnan	7.1	9
5	Feb.4, 1975	19-36	40°42'N 123°0' E	Near Haicheng Liaonin	7.3	9
6	May 29,1976	20-23	24°24'N 98°42'E	Near Longling Yunnan	7.5	9
	May 29,1976	22-00	24°24'N 98°48'E		7.6	
7	July28,1976	03-42	39°24'N 118°06'E	Near Tangshan Hebei	7.8	11
	July28,1976	18-45	39°42'N 118°48'E		7.1	9
8	Aug.16,1976	22-06	32°42'N 104°06'E	Near Songpan Sichuan	7.2	9
	Aug.23,1976	11-30	32°30'N 104°12'E		7.2	

in Haicheng in 1975 affected industrial cities of Yingkuo and Anshan. The Tangshan shock in 1976 occurred in the urban area also cuased damages to a certain degree in Tianjin and Beijing.There has been nothing parallel in the history as to the total amount of economical losses. From this event, we have been convinced that, besides earthquake prediction, we must pay great attention to protect against urban earthquake disasters in order to avoid the reoccurrence of such catastrophe as in Tangshan.

1. General Conditions of Tangshan Earthquake

The focal depth of Tangshan earthquake was about 12-16 km, other parameters being shown in Table 1. The macroepicenter was located in down town area south to Tangshan railway. The peak intensity was grade X1, the area of which was about 47 square kilometers.In gradeX1 area nearly all the buildings were leveled to ground ; Some brick chimneys failed at their lower parts and some water towers supported by brick cylinders failed at the bottoms; reinforced concrete bridge piers ruptured, and bridge decks fell down; A great number of cracks and settlements occurred at ground surfaces;1.5M wide offsets were found in some places; a large amount of underground water spouted out. The intensities were of 1X-X grade in the other area of Tangshan, V11-1X grade in Tianjin and V-V11 grade in Beijing. The area where the intensity was above V11 grade was up to 33,000 square km. The isoseismal map is shown in Fig.1.

In Tangshan, all kinds of structures were severely damaged during the main shock, including about 95% of civil buildings, 80% of industrial buildings. Lots of equipments were destroyed by fallen buildings, underground pipe lines broken, all the brick chimneys damaged. In seismic effected region, about 60% of highway bridges, 40% of railway bridges suffered damage. Rails were bent.Cracks and settlements were observed at the highway surfaces. Earth dams were damaged. The area of sand-boils covered about 24,000 square km, where large area of cultivated fields and more than ten thousand water wells were damaged.A great deal of ground water flew into passageways of Kailuan Coal Mine. The vital systems of the city,including systems of communication, transportation, water supply, power supply and medical treatment were destroyed.

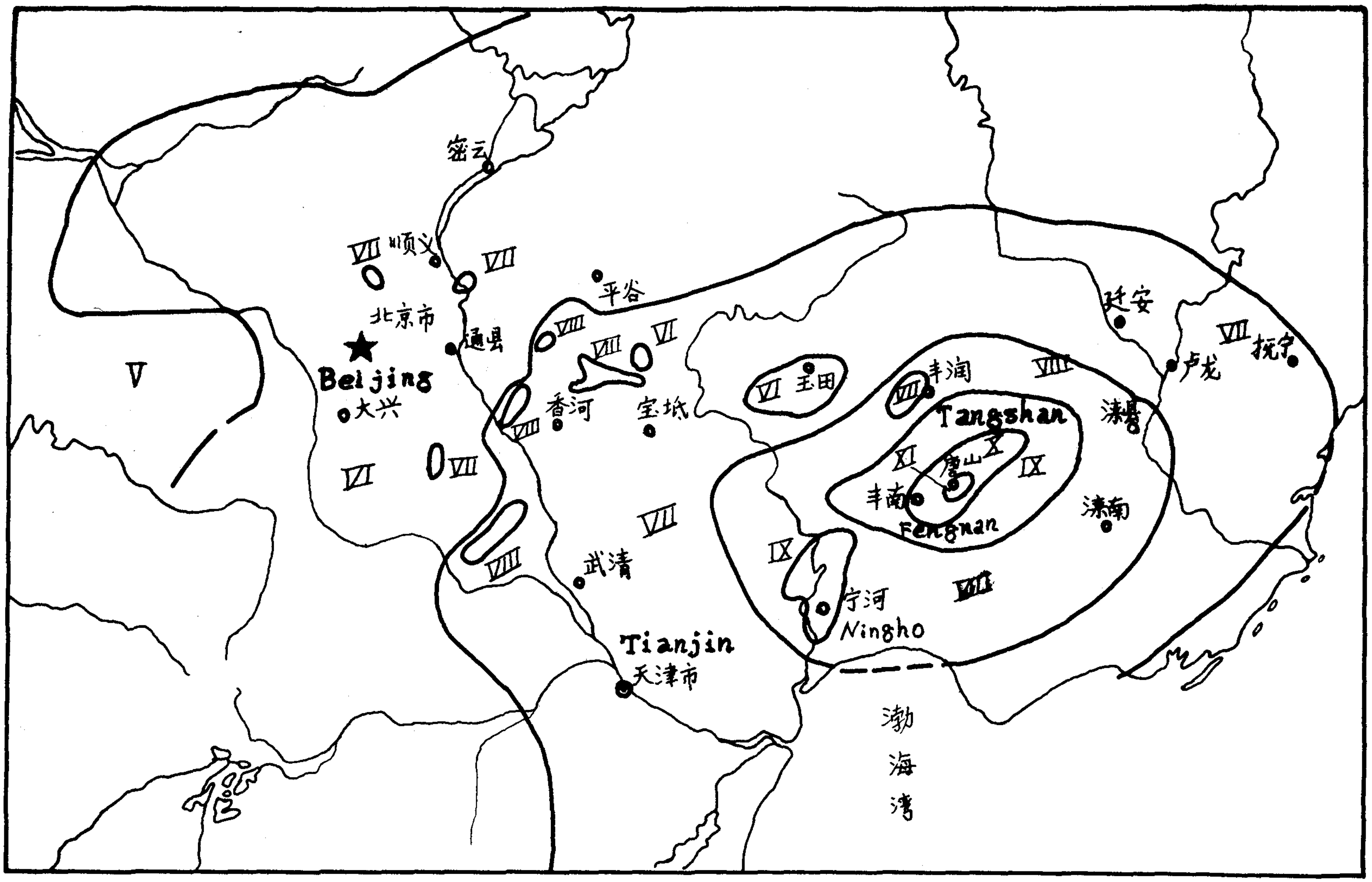


Fig.1 Isoseismal Map of Tangshan Earthquake

From engineering viewpoint, the main causes which led to such a catastrophe are as follows : the basic earthquake intensity of Tangshan region had been assessed too low. According to the requirements of aseismic design code, buildings were not required to be designed to resisting earthquake shock. Hence, nearly all buildings, engineering projects and equipments were lack of earthquake resistance. Most of the brick and prefabricated reinforced concrete structures could not sustain such a strong shock. Soil liquefaction, which had developed over a large area including Tangshan district, southern district of Fengnan and the coast, made the disaster more serious. Accumulative damages were apparent. After the main shock, strong aftershocks of magnitude above 6 occurred 7 times. Especially, the aftershock of 7.1 magnitude in the very afternoon of the same day and the Ningho earthquake of 6.9 magnitude on Nov.15 destroyed most of the buildings which had been damaged but did not collapse in the main shock. For instance, the 800 m long Luanho River Bridge could still be used after the main shock, but during the aftershock of magnitude 7.1, its decks fell down into the river. The fact that the epicentral area was located in the densely inhabited city area naturally had made the damages more serious.

2. Some Engineering Experience from Earthquake in Tangshan

After the earthquake in Tangshan, extensive field observations and investigations were carried out by many professional contingents, from which some engineering experience has been summarized with respect to urban control in earthquake disaster. The following points are given:

A. Buildings

Collapse of buildings was the main cause of losses, injuries and damages of equipments. Therefore, analysis of failure mechanism of buildings and measures to prevent collapse become an urgent subject for mitigating seismic disasters.

In Tangshan, hundreds of multi-storey brick buildings collapsed mainly as a result of spread of shear cracks on load bearing wall . (Figs.2,3 a,b) However,

Fig. 2 Shear cracks occurred diagonally in walls of a multi-storey brick building

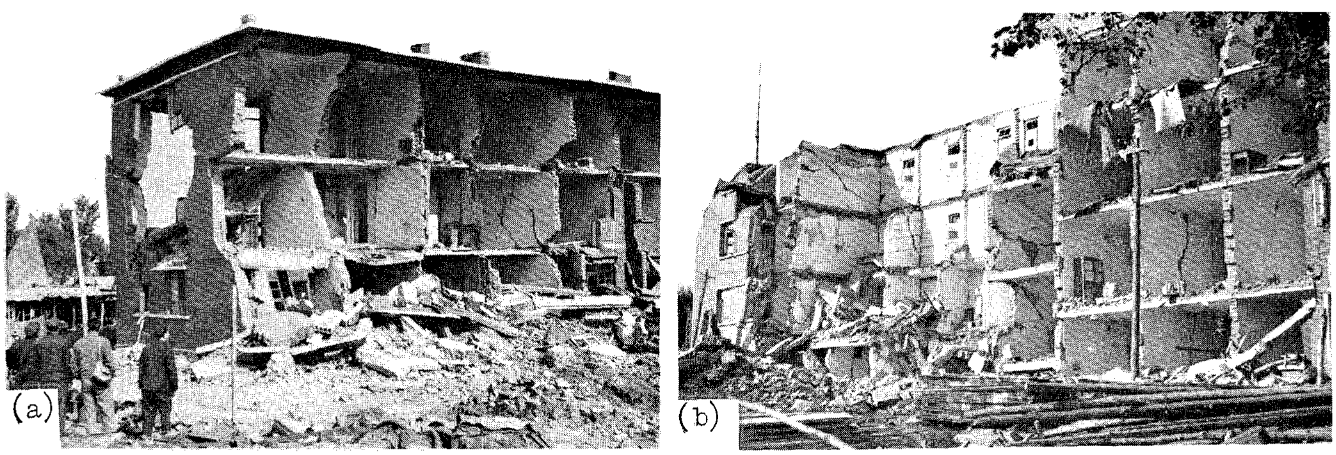


Fig.3 Collapse of a multi-story brick building

a few brick buildings did not collapse, because reinforced concrete columns, connected with closed ringbeams at each floor, were provided at the junctions of longitudinal and transversal walls.(Fig.4) Model test of wall elements and whole building conducted by several institutions after the earthquake also showed that

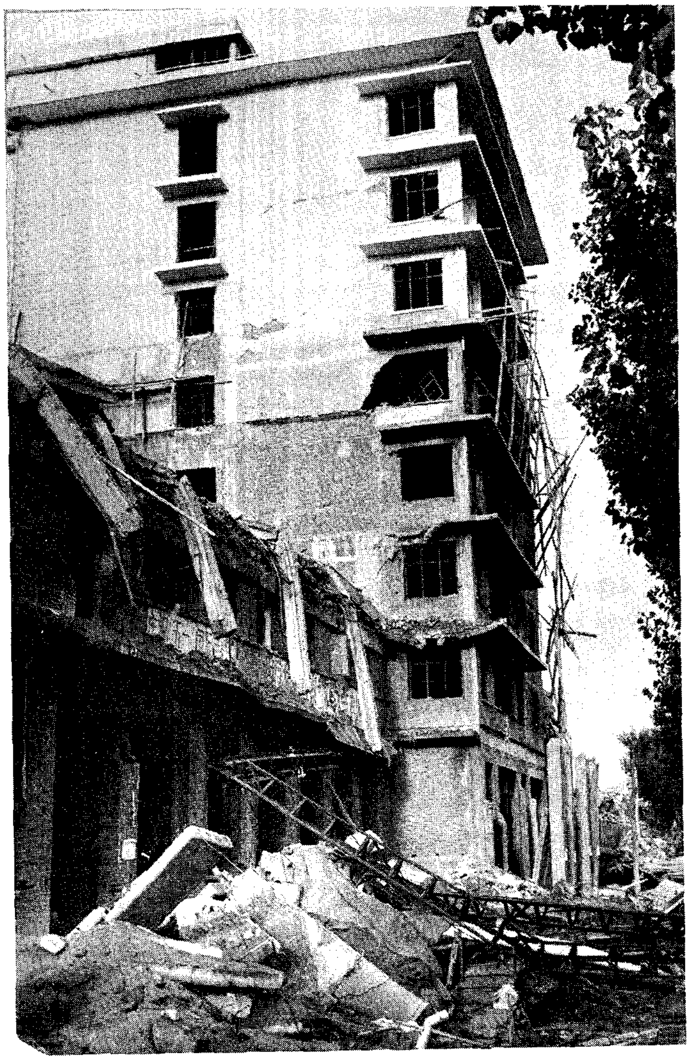


Fig.4 Multi-storey brick building with reinforced concrete columns and tie beams

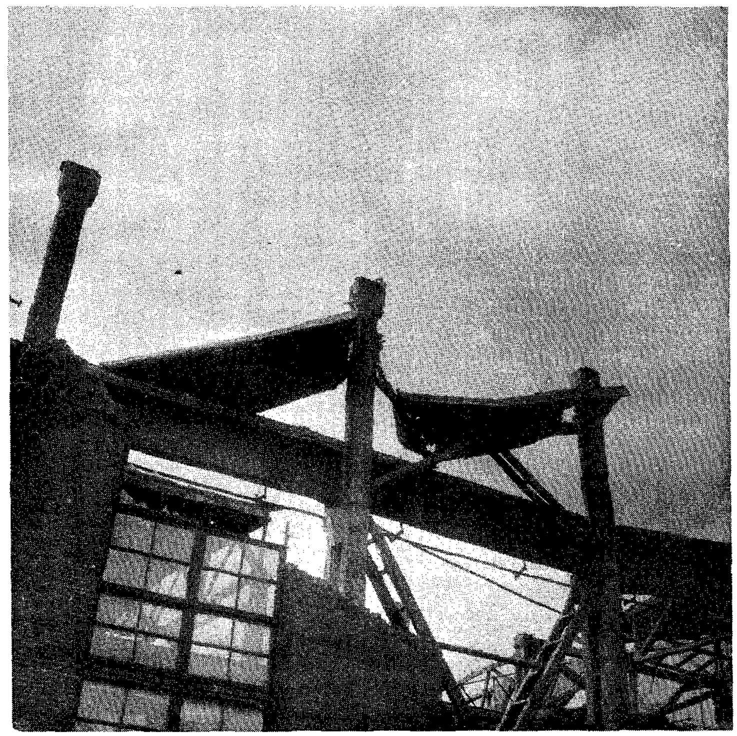


Fig.5 Roof structure fallen due to damage of connections and insufficient diagnal braces

the above measure in bounding brick masonry could confine and delay the spread of shear cracks and increase the capability of preventing collapse.

Prefabricated reinforced concrete single-storey industrial buildings collapsed to a large extent in the area where the intensities of earthquake were of grade V111-X1. In region of high intensity, roof structures fell down due to breaks of columns at the bottom or at the points of cross-sectional change. Weakness of bracing systems between roof frames and between columns caused buildings to collapse longitudinally. Weak connections between roof frame and column, between roof panel and frame as well as overturning of load bearing gable walls at end bays, were also causes of collapse. (Figs. 5,6,7) However, generally no collapse occurred

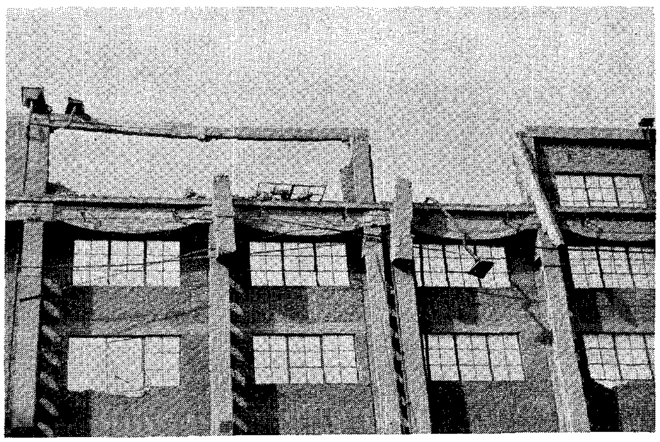


Fig. 6 Roof structure fallen due to rupture in upper parts of columns

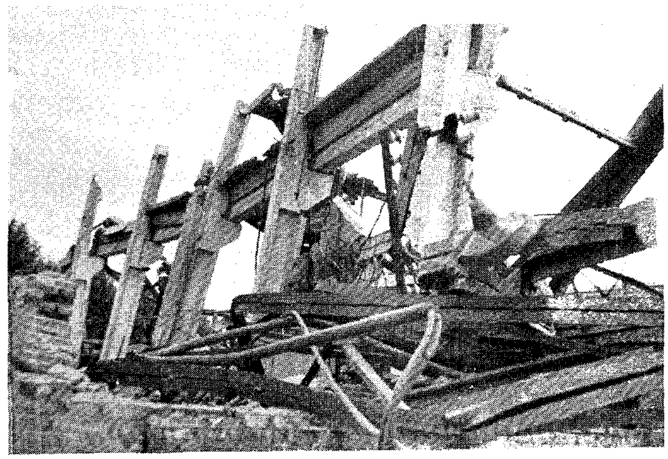


Fig. 7 Columns overturned and building collapsed due to ruptured column bottom

in industrial buildings with strong columns, lightweight roofs and perfect bracing systems, as well as in buildings with folded plate roofs. Therefore, it can be seen that bracing systems, connections and columns are the key points to protect these buildings from collapse. Industrial buildings with unreinforced brick columns often failed due to ruptures at lower portions or partial failure of columns, showing little capability of earthquake resistance. (Figs. 8,9)

In the area where the intensities of earthquake were of grade X-X1, the percentage of reinforced concrete frame structures collapsed was not high, but most of the structures were seriously damaged. Collapse of frame structures were all correlated with column ruptures. Column damages are : horizontal cracks at tops and bottoms, buckling of main bars, shear cracks on column shafts, sliding of steel bars due to stripping of

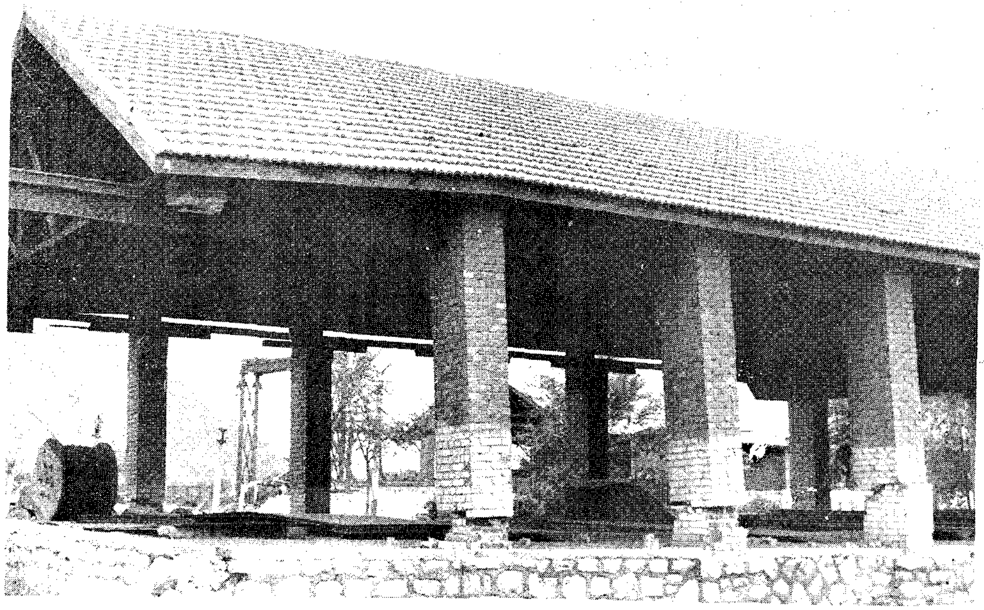


Fig. 8 Shear failure at the lower part of brick column

Fig.9 The lower parts of the columns crashed and fell

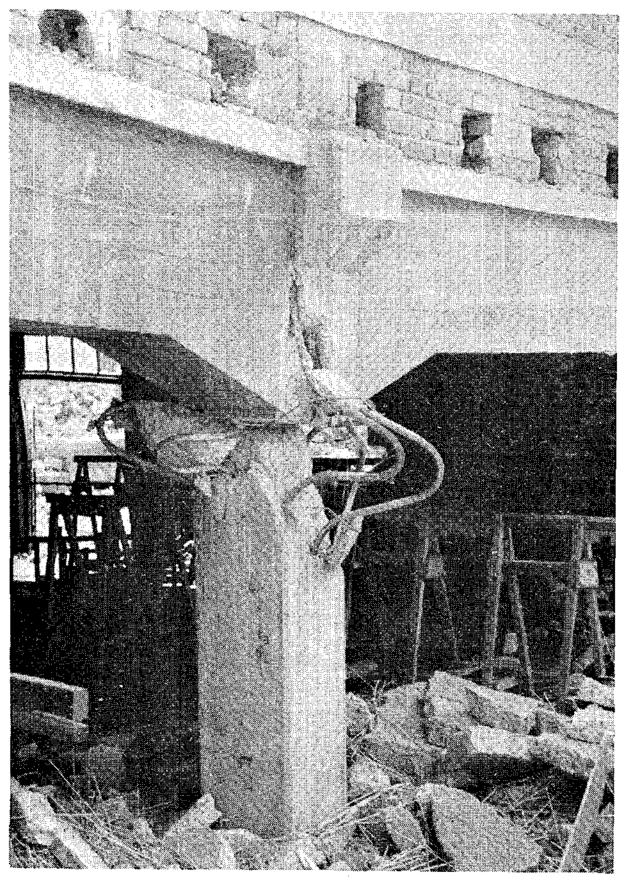
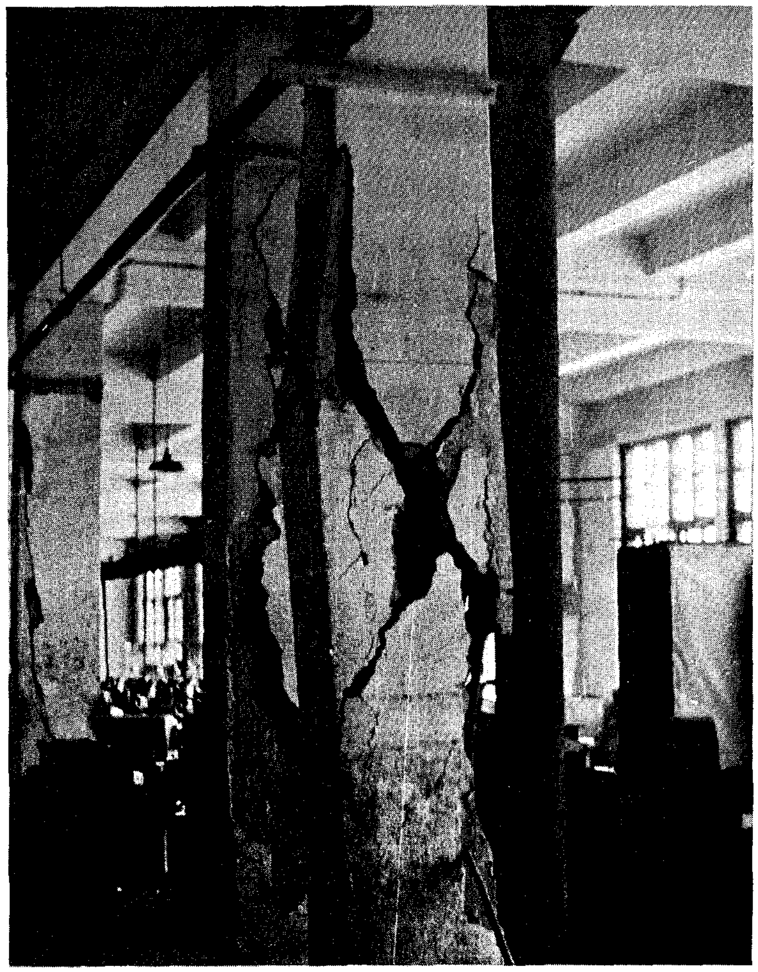


Fig.10 Buckling of main reinforcements

concrete covers (Figs. 10 ,11). A few frame structures either filled with solid brick walls or reinforced concrete panels, which acted as shear walls, did not collapse. (Fig.12) In a two-storey flat slab structure supported by columns with spiral reinforcements, the ground floor did not fail, showing the aseismic effect of the spiral reinforcements(Fig.13).

Fig.11 Shear cracks in a column shaft



In the area where the intensities were of grade X-X1, underground structures were slightly damaged,while nearly all the buildings above ground were leveled to the ground. Moreover, the buildings with basements had slighter damages than those without. The degree of damage of the underground structures was related to the nature of surrounding soils. Generally, buildings on soft soils suffered more. Besides, attention should be paid to entrances which might be blocked by ruins.

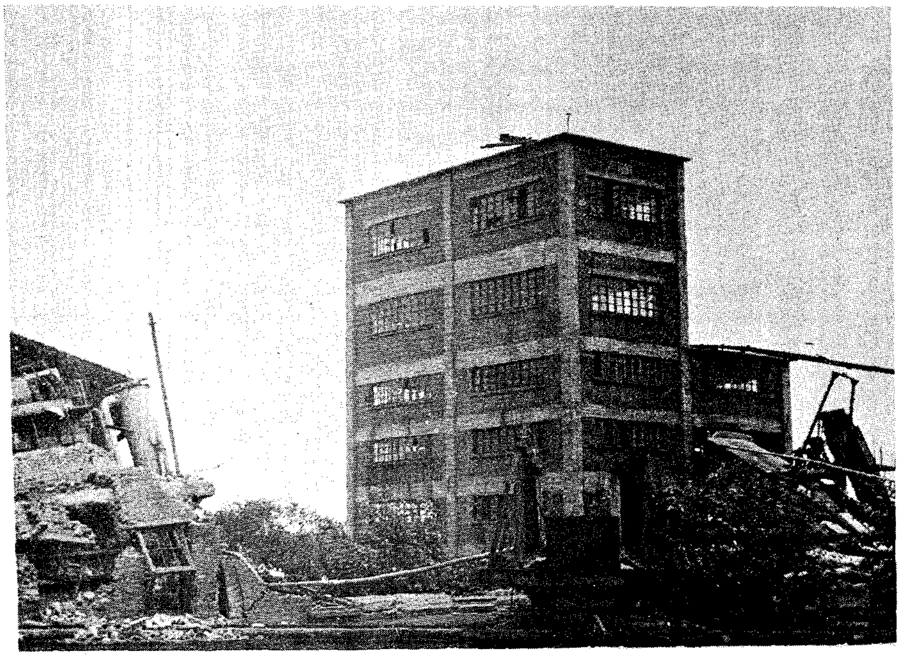


Fig. 12 Multi-storey reinforced concrete frame structure filled with brick wall

Fig. 13 Collapse of a two-story building with flat slabs supported by columns with spiral reinforcements

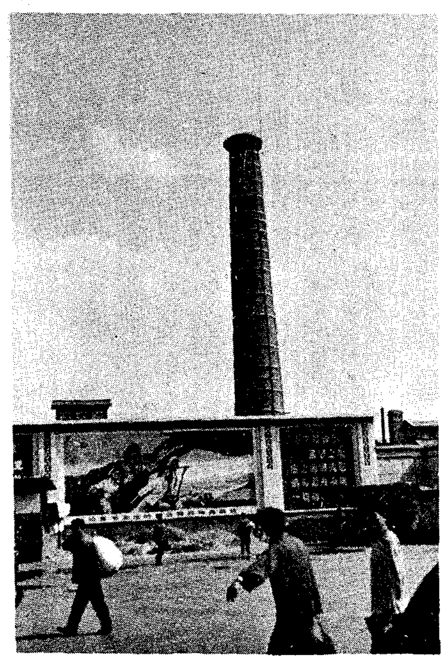


Fig. 14 A brick chimney strengthened by means of steel straps

There were ten thousamd chimneys in Tangshan seismic areas, of which nearly all were destroyed. Even those with horizontal and vertical reinforcements in motar joints at the upper portion were broken at that height and fell down in sections. But the brick chimneys with vertical reinforcements anchored to ring beams were intact. Well anchored vertical reinforcements proved to be effective. Chimneys strengthened with vertical and circumferencial steel angles or straps had no damage. This provides us with a successful experience of strengthening existing brick chimneys (Fig. 14).

A few chimneys in the seismic area were in reinforced concrete. Those below 100 m high were intact. One of 180 m high, located in the area of grade 1X, being designed according to grade V11, thus incapable of resisting strong shock, broke at the height of 132 m during the main shock, and fell down in the aftershock of magnitude7.1. (Fig. 15) Few of the round silos for grain storage in mud and brick in the area of grade 1X-X were damaged, except the old ones. It indicates that round low structures have a good behavior in earthquake resistance.

Records of ground motions registered in Beijing and other places during the main shock and the aftershocks showed that the ratios of accelerations of vertical and horizontal motions ranged from 2/3 to 1. Many horizontal cracks occurred in reinforced concrete columns and brick chimneys might be due to the large components of vertical accelerations.

B. Life Line Systems

Once the life line systems, such as power supply, water supply, communication and transportation facilities are destroyed, the whole city will be paralyzed. Therefore, safeguarding the security of life lines is very important to relieve disasters and recover production.

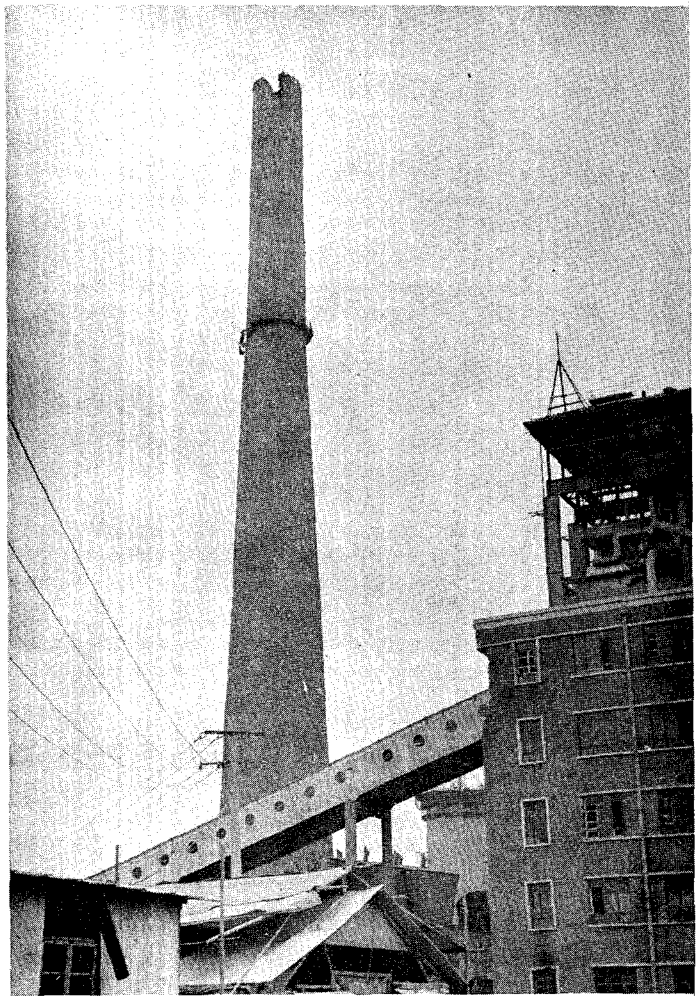


Fig. 15 180m high reinforced concrete chimney broke at the upper portion

Interruption of power supply in Tangshan was substantially caused by collapse of the buildings of power plants and substations as well as by damages to equipments. Transmission lines and equipments with good aseismic behavior located in the open air or in the basements were slightly damaged. After the event, the recovery of power supply mainly relied on the transmission network of Beijin-Tianjin-Tangshan.

From the above analysis, aseismic measures for safeguarding power supply are suggested as follows:

--Security of main buildings;

--Aseismic measures for equipments themselves, with their locations in the open air or basements as far as possible;

--High voltage transmission lines, double power supply lines, and closed transmission network;

--Provision of alternate power supply;

Interrûption of water supply in Tangshan was mainly caused by collapse of water supply structures : water works, water towers and underground pipelines.A lot of lines and ducts, buried under collapsed buildings, could not be repaired.

The Tangshan earthquake showed that the following preventive measures should be taken:

--Security of water supply structures and installations;

--Seperate water sources for different zones;

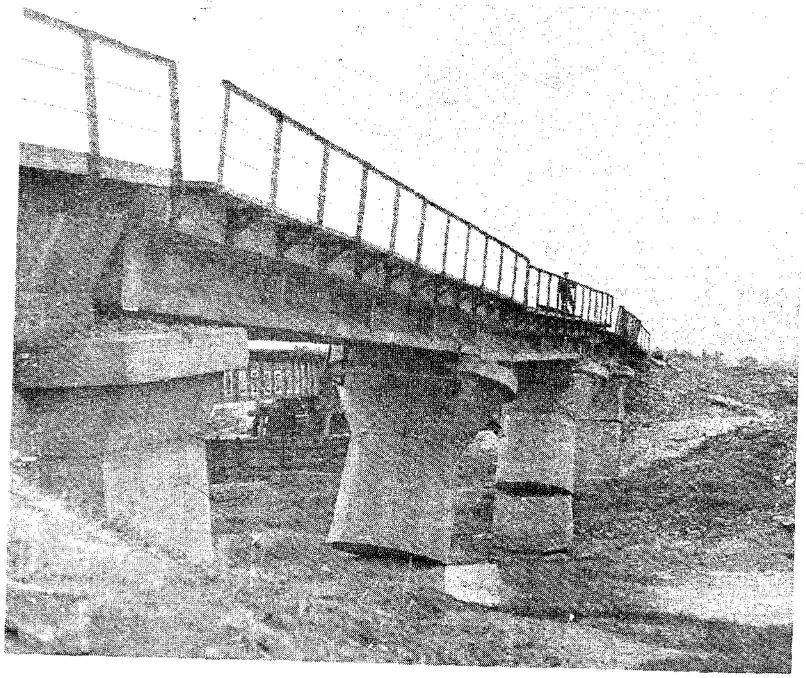
--Supply lines in closed network;

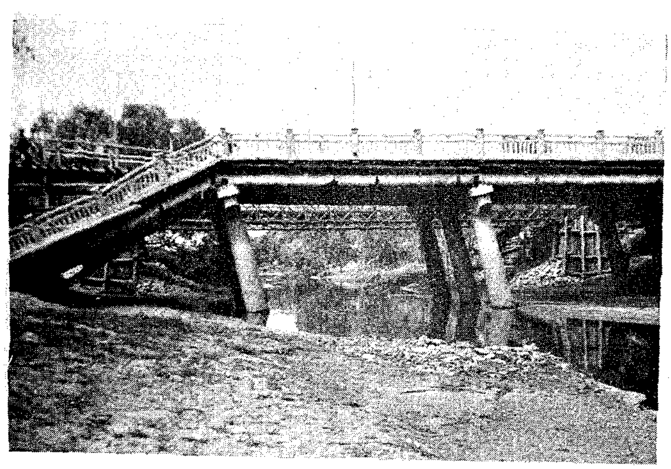
--Flexible joints between pipes;

--Water mains to be far from buildings.

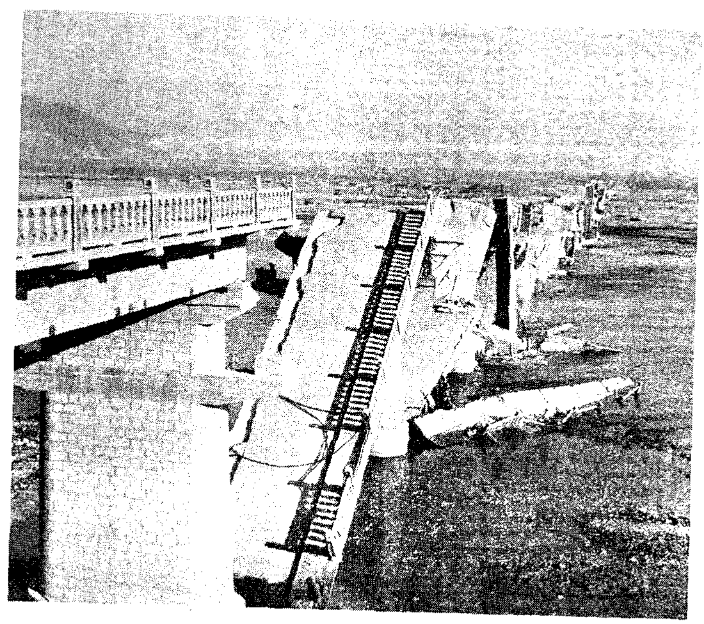
The main causes of communication interruption in Tangshan are:collapse of buildings,damage of lines and poles. At that time, recovery of communication mainly relied upon underground cables which were intact.It can be seen that security of communication buildings and relevant aseismic measures for the equipments and lines are important to ensure normal communications.

The main reason of traffic interruption was damages of roads and bridges. Embankment settlements and landslips occurred on roads, and bent of rails in railways. About 69 and 171 km of main lines of Jing- Shan and Tung-Tuo railways were destroyed respectively. Bridges were severely damaged, with abutments pushed toward the river, piers broken, beams displaced and fallen.(Figs.16,17,a,b) The bridges on Giyunho Canal and Luanho River, as gates of Tangshan, were destroyed.





(a)



(b)

Fig. 17 Bridge beams fell down

The traffic was recoverd only after pontoon were laid.

It manifests that measures to prevent bridges from collapse are: selection of a site on hard soil; broad abutment heads or stoppers to prevent beams from falling; construction of bank protection;deep group - piles,tie beams between foundations of piers to avoid damages due to slippage of river bank; integrity of beams and decks, anchorage of supports, etc.

C. Secondary Disasters

Tangshan is a coal mine base in our country.After the main shock, nearly thirty thousand people working underground safely returned to the ground. But the underground passageways were inundated with water, which was 1.7 to 5 times the usual amount, bringing difficulties to recover production. The maximum gush in a well was up to 160 m^3/min, which would take a year to resume. Hence, secondary power supply and emergency drainage facilities became the focal point for rapid recovery.

In Kaiping Chemical Plant, liquid chloride flew out due to damages to the equipment valves in the workshop. Fortunately, it was diluted by rain water which avoided another catastrophe. Explosions and fires happened in some factories because of damages to containers for chemicals. The collapse of Luanho highway bridge caused breaks of petroleum pipelines between Chinhuangdao and Beijing, bringing pollution to the river. These facts showed that special attention must be paid to cities,particularlly industrial and mining districts, in order to prevent secondary disasters.

D. Equipments

Interruption of life lines and production, occurrence of secondary disasters are all closely related to the damages of equipments.

Most equipments were destroyed as a result of the collapse of buildings. Therefore, security of buildings means protection of equipments. However, we must not neglect damages of equipments themselves, such as displacements of storage tanks and transformers with low centers of gravity; overturning of equipments with high centers of gravity; tearing of pump facilities by connecting pipes; precise instruments being out of order; and rupture of porcelain insulators. (Figs. 18,19) In some cases, molten steel and iron solidified in furnaces as a result of interruptions of power supply, water supply and ventilation. Therefore, equipments should be designed and strengthened according to aseismic design code and relevant norms.

E. Urban Planning

Tangshan is an old city with a history of about 100 years. Dense population and extremely unreasonable urban planning had made the earthquake disaster even heavier.

The building density of Lunan district in Tangshan was up to 70%. Many people died in narrow lanes. After the event, traffic was blocked up. Vehicles lined up for 10 km out of the city. Within the city, the main traffic north-south was blocked up for more than 10 hours. Buildings in the hillside area in Tangshan suffered less than the other places. It proved that site conditions had great effects on mitigation of earthquake damages. Attention should be given to residential

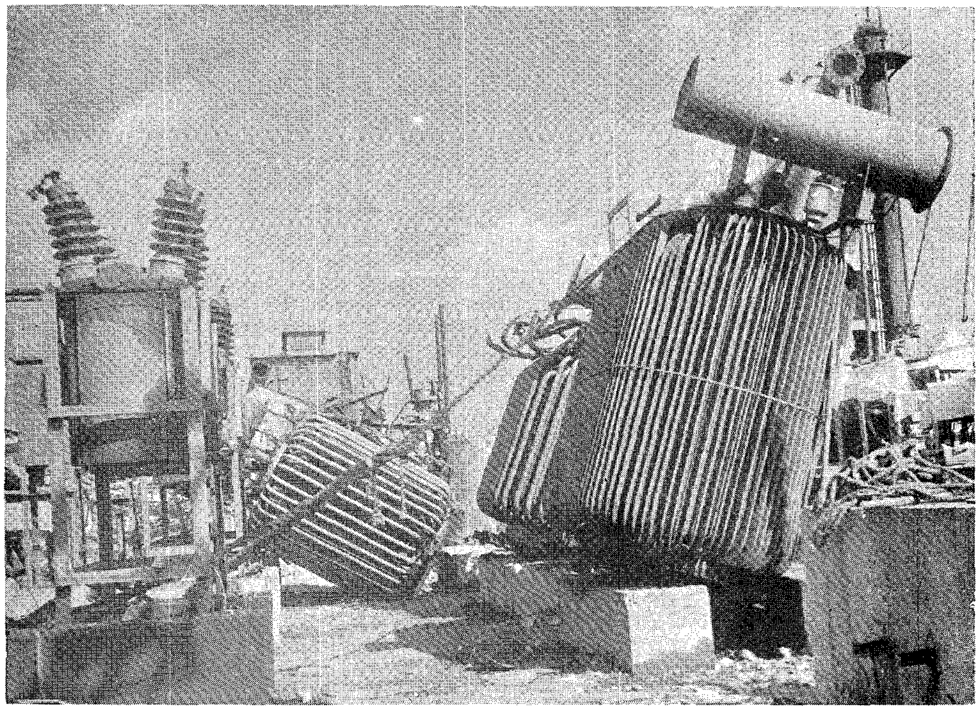


Fig. 18   Overturned transformer

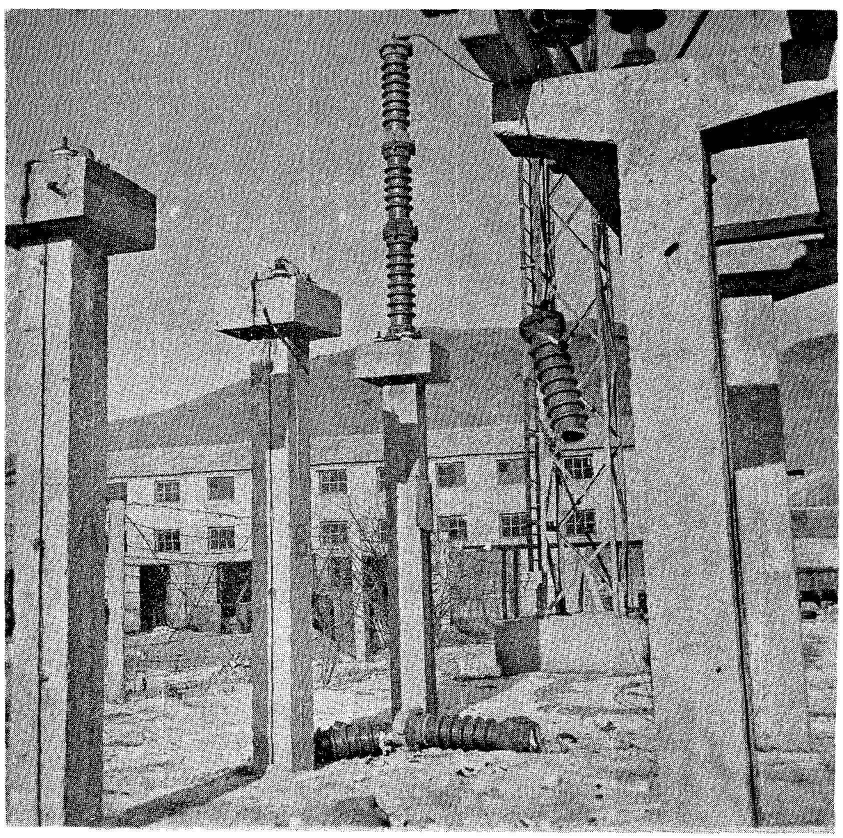


Fig. 19   Ruptured porcelain insulators

districts, roads and land use in planning.

3. Progress of Urban Control of Earthquake Disaster and of Earthquake Engineering

Seismic area with intensity above grade V11 covers about one third of the total area of our country.In this area, there are 38 cities each with a population above 500 thousand, and half of the major national projects will be located. Since the Tangshan event, the following works have been carried out:

A. Repairing and strengthening

A number of buildings in Tianjin, which had been strengthened after 1975 Haicheng shock, suffered little damages during Tangshan earthquake . For instance, over 60,000 square meters of buildings of Tianjin Power Equipment Plant had been strengthened before the event, none of which collapsed during Tangshan earthquake. Most of the buildings in Beijing and Tianjin, which had been strengthened after the main shock, stood well during Ningho shock on November 15 of the same year. Obviously strengthening beforehand and repairing after an shock are effective measures in precaution of earthquake disasters.

The work of repairing damaged buildings has been mainly carried out in Tianjin and Beijing. As to strengthening work in precaution,we have such a large seismic area, Where should we start? The experience of Tangshan earthquake clearly indicated that we must start from the cities which would possibly suffer from strong earthquake according to the medium-range forecast.Thus, some cities were assigned as focal points. Annual plan of strengthening works has been made according to funds and materials supplied by the state,the local governments and the enterprises. Priority will be given to important facilities, vital systems and residential houses of the city. Over forty million square meters of buildings and a great number of engineering facilities and equipments have been strengthened during last two years.

Repairing work must be done in combination with strengthening. A three-storey reinforced concrete frame structure of the Second Wool-Mill of Tianjin is a convincing example. Only simple repair work was done on the columns damaged during the main shock, without any strengthening. As a result,the whole building collapsed during the Ningho earthquake. A national standard,"Evaluation of Earthquake Resistance of Industrial and Civil Buildings" (TJ-23-77)was published in 1977. A series of reinforcement drawings and literature have also been compiled.Other standards of evaluation of earthquake resistance of bridges, municipal engineering and industrial installations will be enforced in the near future.

B. Revision of Aseismic Design Code

Tangshan First Flour Mill, a five-storey reinforced concrete frame structure, located in the area of grade X, was constructed according to the design intensity of grade V111. It is one of a few buildings designed according to aseismic code in Tangshan. After the shock, only little damage was observed. This indicates that the aseimic design is effective.

"Aseismic Design Code for Industrial and Civil

Buildings" (TJ-11-74) published in 1974 has been revised after 1976 shock. The principal revisions are:raise of the standard of earthquake resistance by taking basic intensity as the design intensity for ordinary buildings instead of one grade lower;consideration of liquefaction of satuated sandy loam (particles larger than 0,05 mm in diameter above 40% by weight of the total); revision and reclassification of structural influence coefficients; vertical seismic loads on buildings also considered in area of intensity grade V111, besides buildings in grade 1X; replenishment of aseismic construction measures based on experiences from Tangshan. The new code (TJ-11-78) has been enforced since Aug. 1 this year. Aseismic design codes for hydraulic structures, roads and bridges, municipal engineering will be published before long.

C. Progress of Research Work on Earthquake Engineering

After Tangshan earthquake, contingents of research workers on earthquake engineering have been enlarged and new institutions founded. Earthquake engineering committee of Architectural society of China was founded on May 1978.

Research on strengthening measures has become the most urgent subject after Tangshan event, with stress on multi-storey brick buildings and single-storey industrial buildings. The methods for strengthening multi-storey brick buildings widely used in our country are:addition of brick walls, reinforcing meshes with cement motar to the wall surfaces, ring beams,rods and columns with tie beams. (Figs.20,21)

Development plan of earthquake engineering of our country was made in 1978. Observation of strong-motion of

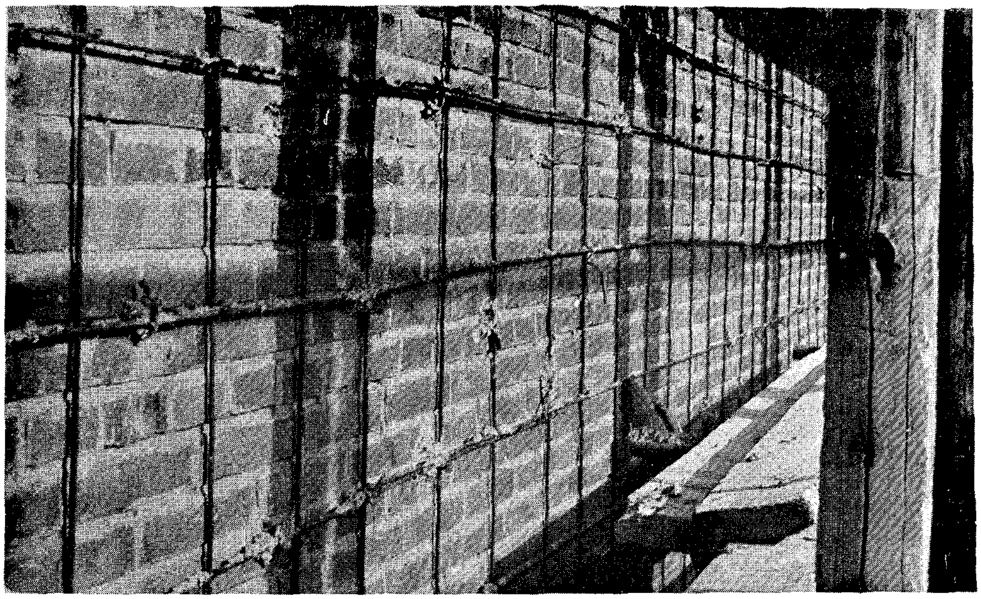


Fig.20 Reinforcing meshes with cement motar added to the wall surface

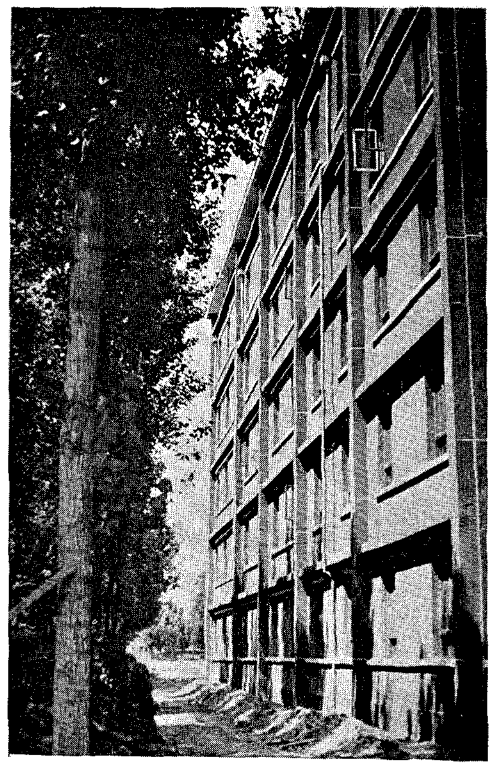


Fig.21 Building strengthened by means of reinforced concrete columns and tie beams

earthquake is the basis for scientific research in the earthquake engineering. At present, there are only a hundred or more strong-motion seismographs in our country. Records of strong ground motion near the epicentral region have not been registered yet. A network of observation stations in main seismic areas, mobile observation stations, as well as a center of data analysis and information exchange should be built up within 3-5 years according to the plan.

Each destructive earthquake is a test of structures,equipments and underground pipes on a vast scale in the laboratory of Nature. Our plan requires careful study of experience in engineering and thorough analysis of important phenomena of damages from strong earthquakes especially that from Tangshan.

The plan lays emphasis on the development of testing apparatus, such as research and manufacture of shaking table for earthquake simulation and other measuring instruments, as well as on the establishment of testing base.

Urban precaution against disasters is of great importance. The research on earthquake hazard prediction, earthquake resistance of urban vital systems and evaluation and strengthening of existing buildings in Beijing and Tianjin as well as other important cities have been included in the plan.

Correct assessment of seismic risk and preventive measures against building collapse are important sub - jects of study arisen from Tangshan earthquake. Fundamental research has been emphasized in the plan, such as characteristics of strong ground motion and its prediction, structural failure mechanism, response analysis, soil dynamics,etc. The plan also require a systematic study of dynamic Behavior of materials, components and structures, aseismic measures for various kinds of structures according to our own conditions. The aseismic design codes and evaluation standards will be updated on the basis of new experiences and results obtained.

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SOME ENGINEERING FEATURES
OF THE 1976 TANGSHAN EARTHQUAKE

by

Hu Yuxian*

Abstract

Some engineering features of the 1976 Tangshan earthquake are presented in the following aspects: seismologic and geologic aspect, damage of structures, intactness of structures not designed for earthquake, failure of smokestacks, strong motion records, and general conclusions added. Considerations are given to general description of the engineering aspects as well as particular features of the earthquake.

1. Seismologic and Geologic Aspect

A strong earthquake of m 7.8 occurred at Tangshan City on the early morning of July 28, 1976. Tangshan is located in the transition of the Northern China Plain on the south to the Serra Yan on the north.

Isoseismals of the main shock were shown in Fig. 1, together with those of a large aftershock and several areas of intensity anomaly. The largest low abnormal intensity area is at Yutien County, where low anomaly usually occurred in historical earthquakes. The most important and common factor of anomaly is the local soil condition.

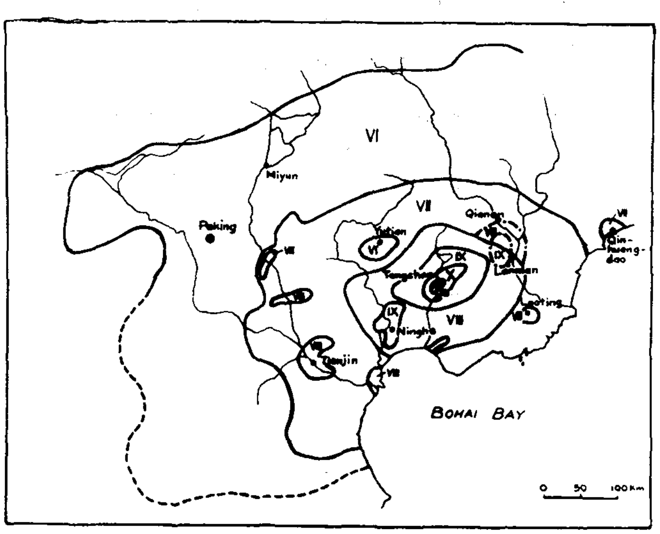

Fig.1 Tangshan Earthquake
1976,7,28 Ms=7.8, I =XI, h=15km

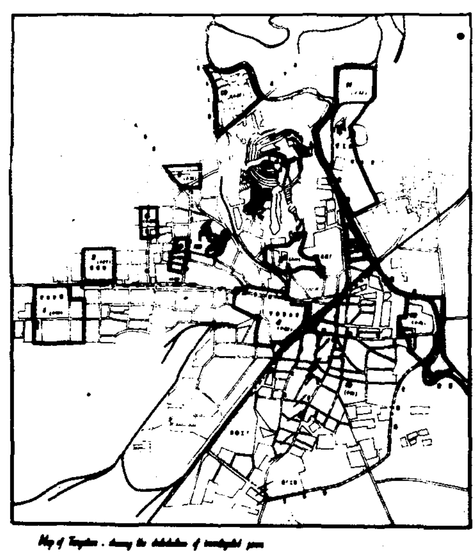

Fig. 2

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A series of ground cracks formed a NE-SW extending earthquake rupture band of a gross length about 10 km, with its NE end in Tangshan City and continued intermittently in the SW dirention to the Fengnan County. Fig. 2 shows a sketch of the Tangshan City and the north end of the rupture band. Highways, roads, rows of trees and poles, and property walls acrossing this band were off-set in a right lateral sense up to 1.5 m. Detailed analyses of seismological, geological and geophysical data showed that the main shock was caused by a complicated fracture process of an old fault, approximately in NE direction, with large right lateral slip and some vertical movement (SE side down, and NW side up). Fig. 3 shows known faults and large aftershocks.

Sandblows were taken as an indication of liquefaction of sandy soils in field, which concentrated as usual along rivers and old river channels or over those places of loose sandy layers near ground surface with high water table. See Fig. 4.

During the 1975 Haicheng earthquake, it was found that a special site condition, i.e. a sufficiently hard layer of clayey soils over a liquefiable sand or soft layer, may reduce the ground surface motion and thus protect the structures above. There were some examples in the Tangshan earthquake again, as shown in Photo 1, which shows some of the village adobe houses in Ning-he County of intensity IX with almost no damage.

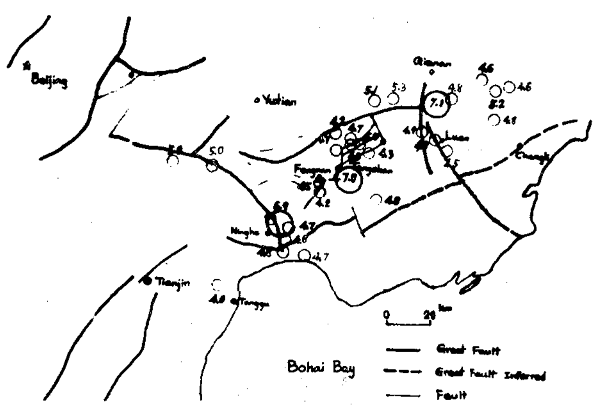


Fig. 3

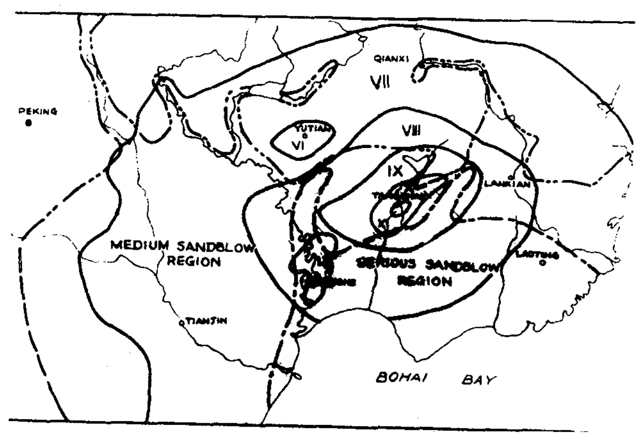


Fig. 4

2. Damage to Structures

Most structures in Tangshan area were not designed for earthquake because the max. intensity expected there before was only VI on our intensity scale. Fig. 5 shows a map of major earthquakes near Tangshan area before the 1975 earthquake. For construction before 1975, i.e. for long-term earthquake prediction, we did not expect an earthquake to occur near Tangshan and the design intensity in Tangshan area was taken as VI caused by some possible earthquake at Luan County (Fig. 5).

The great loss caused by the unexpected 1975 earthquake aroused a strong discussion among engineers on the balance of safety and economy in protecting people from the unexpected strong earthquake. This problem has to be solved with some subjective decisions now and a reasonable solution should take into consideration the uncertainties involved in earthquake prediction, assesment of ground motion and other aspects on one hand and chance of various extents of damage tolerable to the public on the other with objective decisions.

Tables 1-5 show some statistics of ordinary structures inspected by IEM members. They are given here rather as typical examples than as general percentages since we investigated only a portion, not all, of structures.

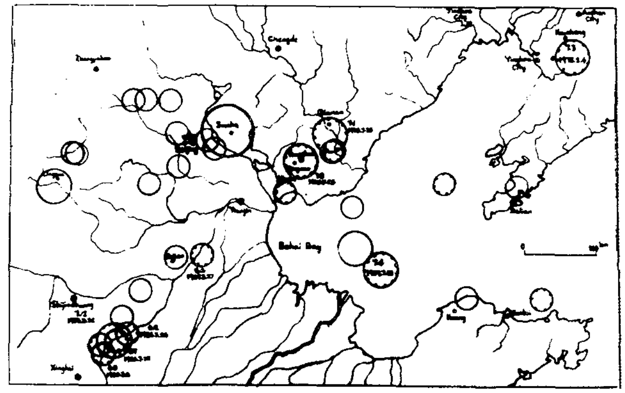


Fig. 5

Table 1
Damage of Industrial Bldgs in Percentages

Intensity	XI					X					IX					VIII					VII				
Damage Level	C	H	M	S	I	C	H	M	S	I	C	H	M	S	I	C	H	M	S	I	C	H	M	S	I
Single-story with																									
R.C.Columns	70	23			07	25	32	4	10	29			33	67											100
Brick Columns	87	9		4		58	17	11	11	3	90	5			5	20	15	10	30	25	3	15	32	24	26
Steel Columns	75				25			50		50															
R.C.Frame						36	29	21	7	7		72	14	14											
Multi-story																									
Brick Bldgs																					40		20	40	

C(collapse)--total collapse of structural elements
H(heavy)--damage of structural elements beyond repair
M(medium)--obvious damage of structural elements to such an extent that repairs are needed.
S(slight)--almost no damage to structural elements but obvious damage to non-structural elements.
I(intact)--almost no damage to whole structure

An important lesson learned for mill buildings is that failure of roof systems (Photo 2) is one of the main causes for the heavy losses and it is therefore very desirable to design the bracings, connections between roof and column, to insure the integrety and stability if the roof. For mill buildings designed not for earthquake, there were bracing rods buckled even at intensity VI and roofs fallen at intensity VIII. For structures with good roof bracings and their connection details, the roof systems survived this earthquake quite well. Column failure is another important cause of structural collapse, as shown in Photo 3.

It is felt that structures or components of a structure should be designed with clearly defined, different factors of safely or probability of failure according to the failure consequence.

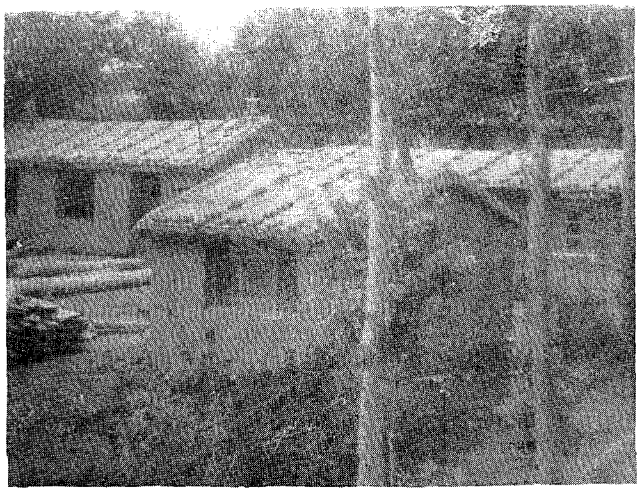


Photo 1. Undamaged Adobe Houses, Ning-he County, Intensity IX.

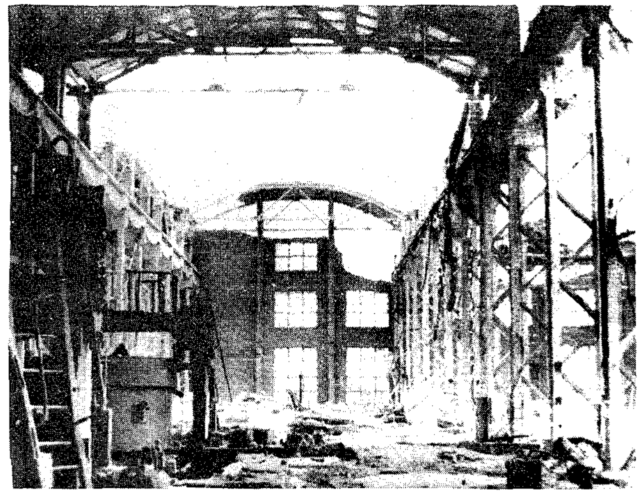


Photo 2. Failed Roof System.

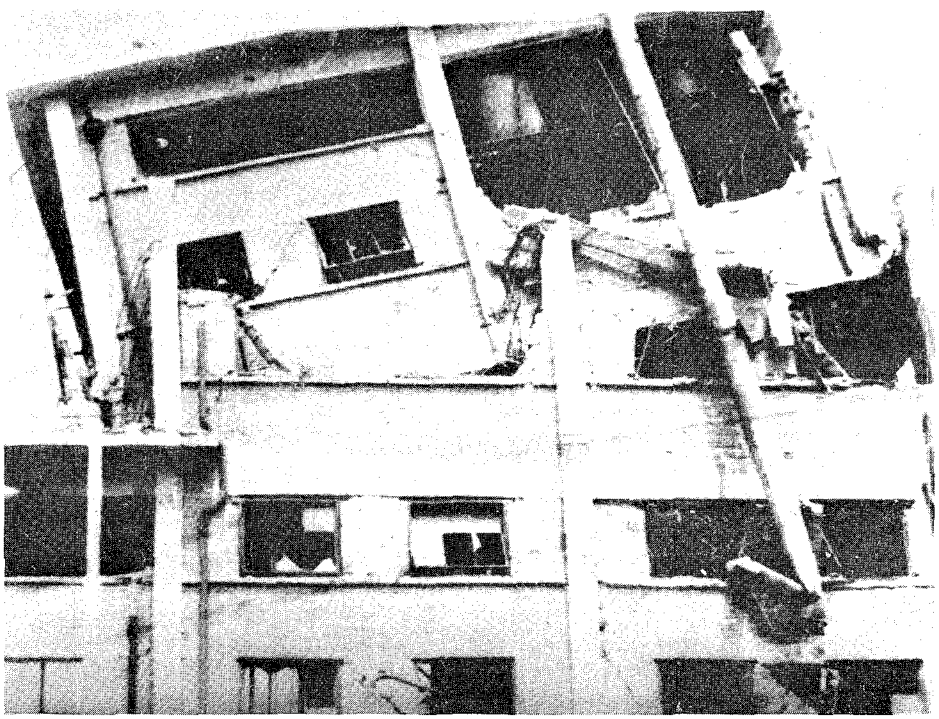


Photo 3. Column Failure.

Table 2
Non-industrial Multi-story Brick Bldgs
Damage in Percentages

Damage Level	Collapse	Heavy	Medium	Slight	Intact
Intensity XI	96	4			
X	76	22	2		
IX	22	34	22	22	
VIII	8	23	15	15	39
VII		33	45	11	11

Table 3
Elevated Water Tanks on Un-reinforced Brick Cylindric Shaft
Damage in Percentages

Damage Level	Collapse	Heavy	Medium	Slight	Intact
Intensity XI	100				
X	63	25			12
IX	78	11	11		
VIII	25	25	33	17	
VII		30	35	18	17

Table 4
Un-reinforced Brick Smokestacks
Damage in Percentages

Damage Level	Collapse	Heavy	Medium	Slight	Intact
Intensity XI	100				
X	76	11	13		
IX	100				
VIII	90		10		
VII	67	11	22		

It is obvious from data in Tables 1-4 that ordinary un-reinforced brick works not designed for earthquake have a large chance to be shaken down by an excitation of intensity IX. New structural materials as well as new structural types are needed for buildings.

Smokestacks were damaged much heavier in Han-gu of intensity IX than in Tangshan of intensity X, since Han-gu is on deep soft ground far away from epicentre. This type of site effect on long-period structures has been pointed in the 1975 Haicheng earthquake as well as in other earthquakes in the world.

While smokestacks were damaged usually in the upper portion, elevated water-tank shafts or mine shafts were damaged usually in the lower. Photos 4 and 5 show a R. C. mine shaft of 12 m diameter and 40 m above ground in the west of Tangshan about 2 km from epicenter. It was broken at first window level, with the upper portion of more than 30 m high dropped 6 m, inserted in the bottom portion and inclined at an angle of about 7° with the vertical.

Three reasons may be mentioned for this difference in failure pattern of smakestacks and elevated tank shafts, namely: effect of first horizontal vibrational mode is more pronounced in case of tank shafts; openings at bottom of tank shaft weaken the shaft cross-section; large compression at top of tank shaft reduces the probable tension stresses and adds some shearing resistance.

Table 5
Damage of Highway Bridges in Percentages

Damage Level	Collapse	Heavy	Medium	Slight	Intact
Intensity X-XI	40	10	20	30	
IX	42	13	13	26	6
VIII		30	19	20	31
VII	5		5	30	60

The most serious harm due to bridge failure came from falling of super-structures to the river or, more usually from sliding or tilting of the abutments (Photos 6 and 7). Saturated fine sand layer is a common cause of failure of bridge on weak grounds while longitudinal dynamic relative movement of piers and abutments is highly suspected for falling of super-structures of bridges on competent grounds. The max. shortening of one span of the bridge in Photo 7 was about 4 m with beams onto the bank due to the sliding of the embankment slope.

3. Intactness of Structures not Designed for Quake

In contrast with the severity of damage, there were some structures, also not designed for earthquake, stood unhurt in a mess of badly damaged buildings. Following examples are taken from intensity X areas.

(1) A Cement Factory (region 8 in Fig. 2)

A cement factory was less than 1 km from the north end of the ground rupture band. Photo 8 shows two identical buildings closely located in the residential quarter of the factory. They were made of pre-stressed hollow slabs supported on un-reinforced brick walls. Only a few fine and local cracks were found on exterior walls near windows and on interior partition walls.

(2) The Tangshan Steel Factory (region 11 in Fig. 2)

Photo 9 shows an elevated water-tank supported on un-reinforced brick cylindrical shaft with buttresses, empty during the earthquake, on which only one crack was found on the shaft at a level about 1 m above ground.

Photo 10 shows one of the 11 buildings with only minor cracks at corners of openings. A thick layer of soft soil a few meters under the foundations may be beneficial to the buildings in absorbing the high-frequency components of incoming waves and safe the buildings.

The real causes and practical consequence of these survived structures may not be clear, but serious consideration on following facotrs seem needed now: effect of bedrock foundation on ground motion, benefit of deep foundation and basement to superstructure, quantitative evaluation of good workmanship of masonry construction.

4. Failure of Smokestacks of Un-reinforced Bricks

Damage observed on smokestacks in areas of intensity VI is often a few cracks with no dislocation, while smokestacks with many horizontal cracks and dislocations were quite often in higher intensity areas (Photo 11). Many times, the dislocations were so large that it would be difficult to imagine how the cracked portions could remain there without falling off (Photos 12-13); but most of the damaged smokestacks had their top portions falling off and with the debris scattered all over the ground not far away from the smokestacks (Photo 14).

The predominance of the closely spaced horizontal cracks and all around debris have aroused a discussion about the failure mechanism of the smokestack and the role of vertical component of the ground motion. Photos 15-17 were presented in a hope that they may give some hints to the answer. It would not be unreasonable to suggest that the possible vertical collision or bouncing effect at horizontal cracks either by rocking or by vertical vibration of the upper portion and probably with simultaneous horizontal pushing of the still contacted portion of the cross-section be studied.

A photo from Tianjin area after this earthquake and another from the 1975 Haicheng earthquake of seldom seen types of failure (Photos 18 and 19) may remind us that a possible event of very little chance may happen if the number of tests is large enough.

Photo 4. Collapsed Mine Shaft.

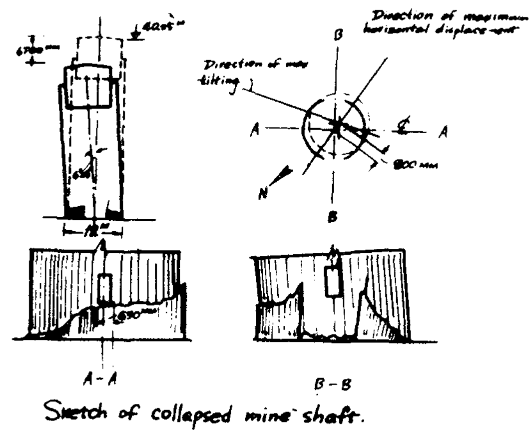


Photo 5. Sketch of Collapsed Mine Shaft.

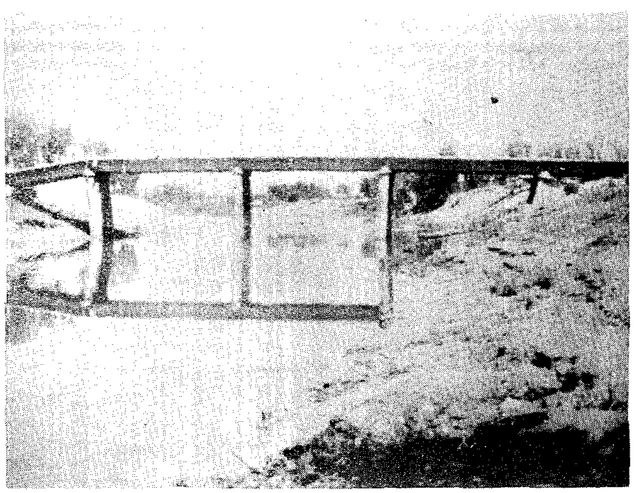


Photo 6. Bridge Damage.

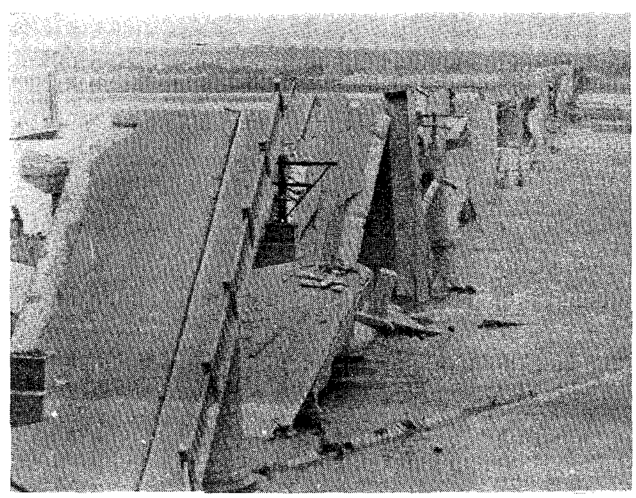


Photo 7. Bridge Damage.

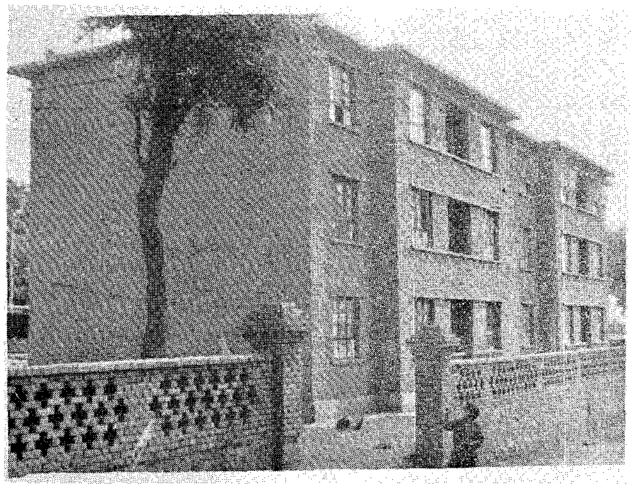


Photo 8. Pre-stressed, Hollow Slab Building on Unreinforced Brick Walls, Region 8, Tangshan. Minor Damage.

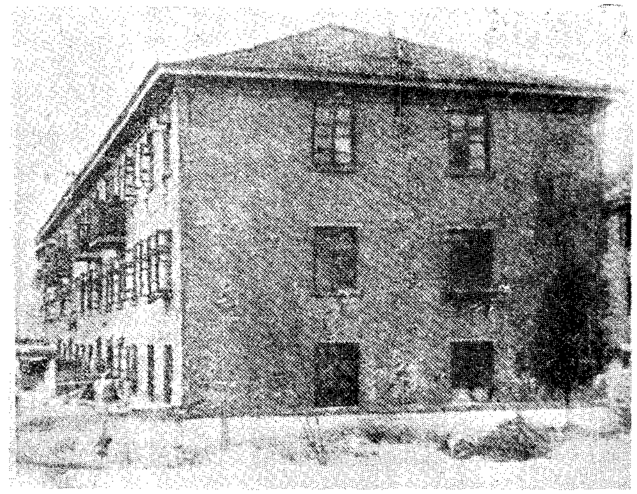


Photo 10. One of 11 Buildings With Minor Cracks.

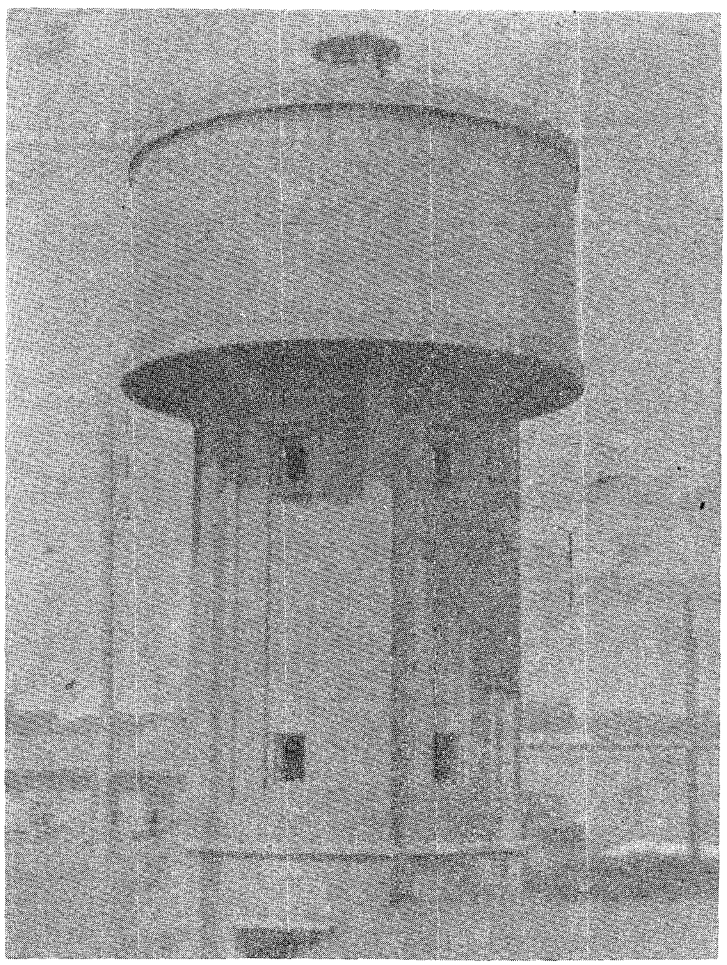


Photo 9. Elevated Water Tank on Unreinforced Brick Shaft.

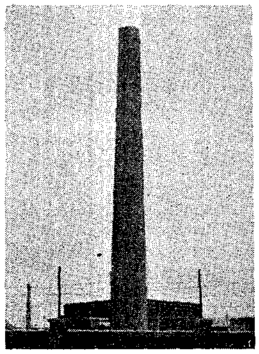


Photo 11.

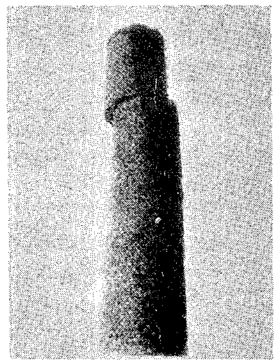


Photo 12.

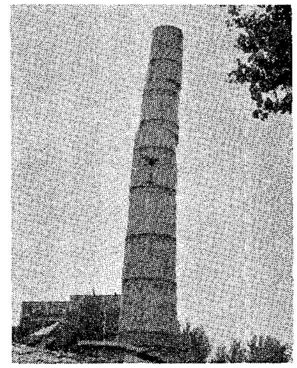


Photo 13.

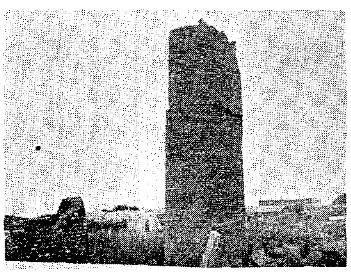


Photo 14.

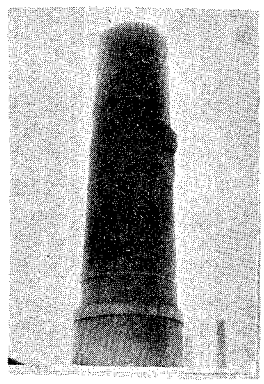
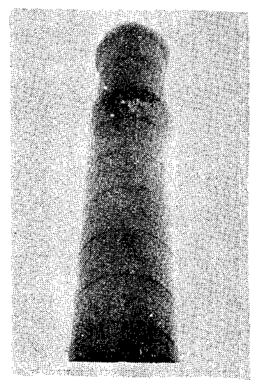


Photo 15.



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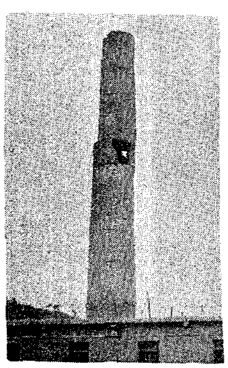


Photo 17.

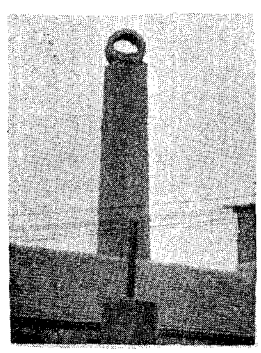


Photo 18.

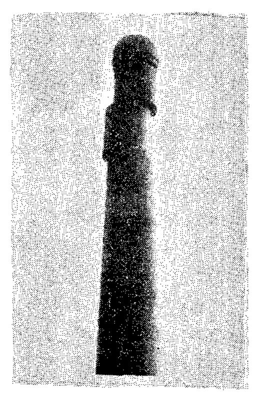


Photo 19.

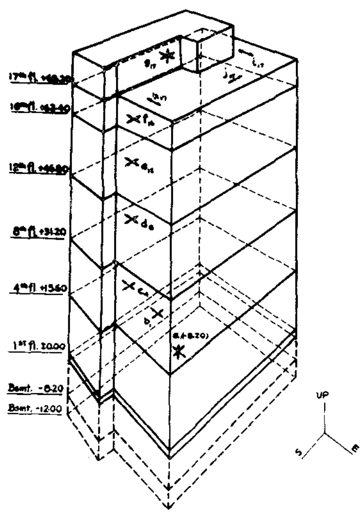
Smokestack Damage (see text).

5. Strong Motion Records Obtained

A series of our accelerographs at Beijing-Tianjin area recorded the main shock on structures and nearby grounds. Specially designed for strong motion observation on structures, each set of our accelerograph provides 12 channels of record with 12 pickups at points where records are designed simultaneously.

Only two examples will be given here. One is the new Beijing Hotel building as shown in Fig. 3 where two sets of accelerographs were allocated and the other is Miyun dam (Fig. 5). Good records of 19 and 12 traces were obtained respectively for the main shock (Figs. 4 and 6) and for a series of strong aftershocks. Simultaneously recorded motions both on structures and on grounds are very valuable for investigation of parameters of the structures as well as of the input motion.

Strong motion records obtained on ground during the Tangshan main-shock show a rather strong vertical component, with max. vertical acceleration about 50-100% of that of the horizontal even at epicenter distance more than 100 km, and a long duration nearly 100 seconds at that distance.



DISTRIBUTION OF PICK UPS IN PEKING HOTEL

Fig. 6

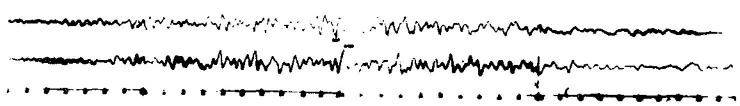


Fig. 7

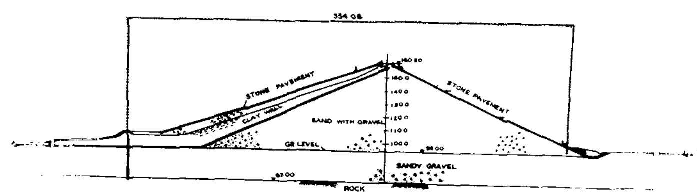


Fig. 8

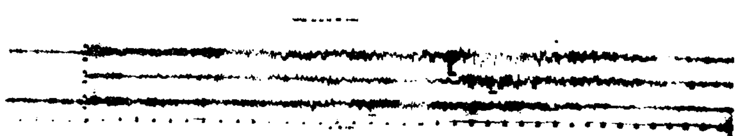


Fig. 9

6. Effectiveness of Strengthening Existing Structures

Many structures in the shaken area have been strengthened before the main shock because of a warning given at the end of 1975 of possible strong earthquake in the next 1 or 2 years. Strengthening was carried out in conforming to our building code and experiences from past strong earthquakes. The Tianjin Power Facility Factory in Tianjin, for example, had their 64 structures inspected and strengthened before May 1, 1976, for an intensity VII. After the main shock, the strengthened structures were damaged much slighter than similar ones of the neighbouring factories not strengthened. Another example, also in Tianjin, is from a building managing and repairing division. Division technicians inspected and strengthened hundreds of low-quality buildings within their responsible area. During the main shock, the strengthened low-quality buildings behaved much better than those unstrengthened "good-quality" buildings.

Effective methods used are generally to add horizontal tie-rods and spandrel beams to hold walls in position for masonry buildings and to strengthen anchors, connections, details, bracings and columns for industrial structures.

7. General Conclusions Added

Many general principles for earthquake-resistant design have been incorporated in our building code. Since the Tangshan earthquake is the greatest one in our country occurred in an industrial area, additional general conclusions may be suggested.

(1) The necessity of designing a structure to stand an earthquake of the expected intensity with nearly no damage and an earthquake much over that with no collapse to save the people and the indispensable things inside.

(2) Popularization of R.C. structures.

(3) Need of a more scientific balance between safety and economy, especially for mill buildings with brick columns or walls common in our country.

(4) Effectiveness of strengthening structures.

(5) Effect of vertical component of ground motion on structural behavior should be seriously studies.

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FIELD PHENOMENA IN MEIZOSEISMAL AREA OF THE 1976 TANGSHAN EARTHQUAKE

by

Chen Dasheng*

The 1976 Tangshan earthquake (Ms= 7.8) is the greatest earthquake ever occurred in a densely populated industrial-mining city in China. Many people above the ground lost their lives due to collapse of structures concentrated in the Tangshan City and its vicinity. In Kailuan Coal Mine all the workers working underground returned to the ground surface safely from several gate ways after the mian shock. Maximum slippages as observed on the ground breakages acrossing the southern part of Tangshan City and Fengnan County were approximately 1.53m horizontal and 0.8m vertical. In meizoseismal area, most buildings and structures on the ground were either totally collapsed or seriously damaged, but the underground structures, including basements, were slightly damaged, except that the branch tunnels along both banks of Dou River were rather heavily damaged.

Field inspections had been carried out by various professional working groups. Some field phenomena observed in meizoseismal area and its vicinity are presented in this paper.

1. Seismological and Geological Aspects

The Tangshan earthquake of July 28, 1976 was considered to be generated by strike slippage on the fifth fault of Tangshan Coal Mine Branch near the northern part of the Ninghe-Tangshan fault. The principal parameters of the main shock are as follows:

Origin time: 0342 Beijing time
Instrumental epicenter: Latitude 39°25'N, Longitude 118°11'E
Macroseismic epicenter: Latitude 39°35.8'N, Longitude 118°11.7'E (in southern part of Tangshan City near Jixiang Road)
Magnitude: 7.8
Maximum intensity: I_0 =XI (Chinese Intensity Scale)
Depth: h=12-16 km

Thousands of aftershocks followed the main event, and the largest one with a magnitude of 7.1 occurred in the northern part of Luanxian County near Xicuigezhuang (Latitude 39°40'N, Longitude 118°34'E) at 18:45 in the same day. Its maximum intensity was determined to be IX.

Isoseismals of the main shock (intensity V and higher) were shown in Fig. 1, together with those of the largest aftershock and several areas of intensity anomaly. The largest area of low intensity anomaly (approximately 306 square kilometers) is in Yutian County

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where such anomaly has been noted in historical earthquakes, for instance, in the 1679 Sanhe-Pinggu earthquake of Magnitude 8. The large areas of high intensity anomaly are Ninghe, Tianjin City, Tanggu, Laoting and Qinghuangdao. Local site condition is a major cause of intensity anomaly. The lengths of major and minor axis and the areas of isoseismals for various intensities of the main shock are listed in Table 1. The main shock was felt over an area of at least 2,167,000 square kilometers, and as far as 1,120 kilometers from Tangshan City. Perceptibility was extended to Heilongjiang Province to the north; Henan Province to the south; Ningxia Province to the west; and Korean Peninsula to the east as shown in Fig. 2.

Table 1

Intensity	Area (km^2)	Length of major axis (km)	Length of minor axis (km)
XI	47	10.5	5.5
X and higher	370	36	15
IX and higher	1,800	78	42
VIII and higher	7,270	120	84
VII and higher	33,300	240	150
V and higher	216,000	600	500

The meizoseismal area (I_0=XI) was within the boundary of Tangshan City as shown in Fig. 3. Three hills Fenghuangshan, Dachengshan And Jiajiashan were all in the northern part of the meizoseismal area.

In the mountainous area north of Tangshan Region, the overburden is rather thin and outcrops of delomite of Sinian Period are found at some places. Outcrops of delomite of Sinian Period and limestone of Canbrian or Ordovician Period scatter widely in the east of Luanxian County, and the thickness of overburden is generally less than 15 m. In the southern plain area the total depth of deposit is up to 800m. The isopach contour map of Quaternary deposit in Tangshan City and its vicinity is shown in Fig. 4. The deposit thickness in Tangshan City increases gradually from northeast to southwest. Outcrops of limestone of Ordovician Period appear on the three hills in the northeast part of the city. The thickness of seposit in Tangshan Power Plant, situated by the hill Dachengshan, is only four meters in depth, but the thickness of deposit in southern part of the city is approximately 500-800m. A typical log is shown in Fig. 5.

According to the data from Tangshan Coal Mine Branch, there are five old faults with northeast strike in overburden within the Tangshan City. The first and the fourth fault are normal faults, and the second, the third and the fifth fault are reverse faults.

2. Ground Breakages

The ground breakages composed of a series of en echelon fractures as shown in Fig. 6 were more than 8km long and was considered to be a result of the underground main faulting of the main shock. The general strike extended approximately in N30°E direction, and the strike of each en echelon fissure varied from N20°E to N60°E direction.

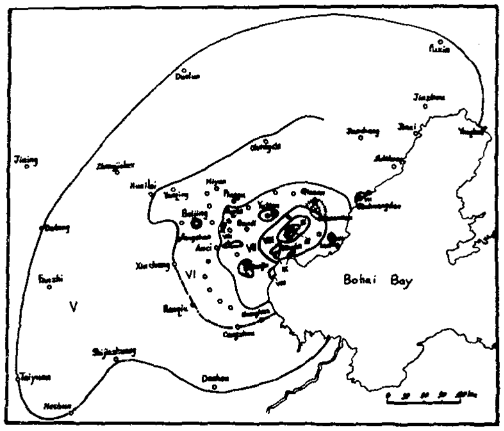


Fig. 1

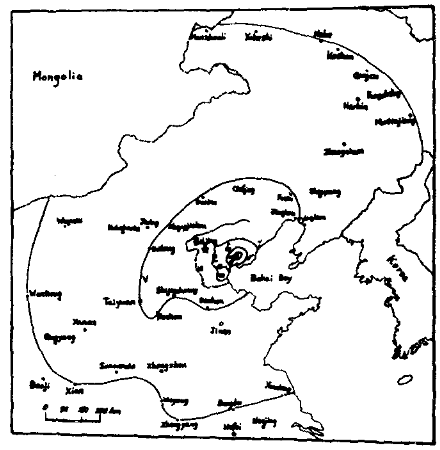


Fig. 2

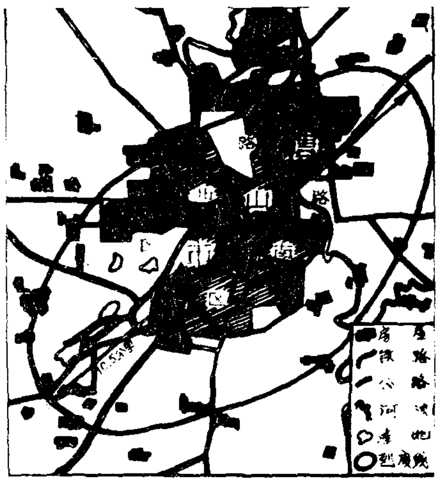


Fig. 3

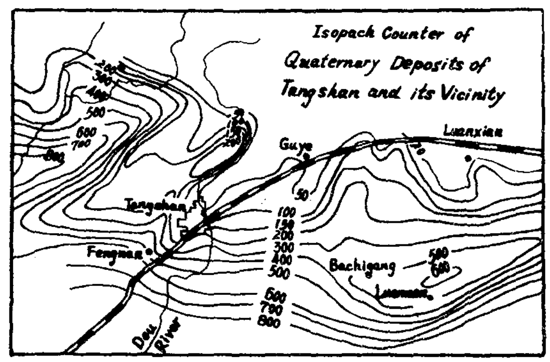


Fig. 4

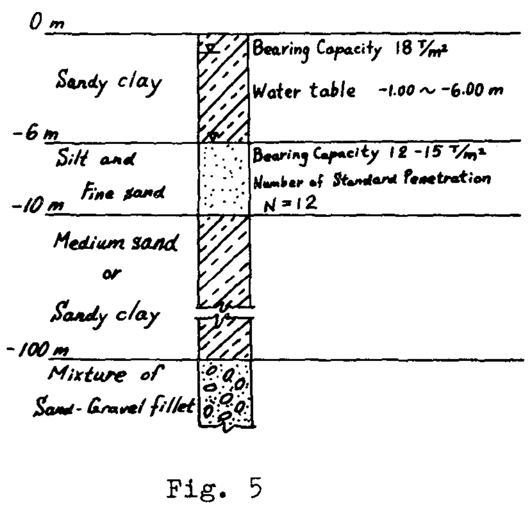


Fig. 5

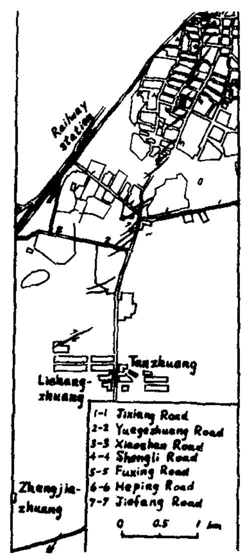


Fig. 6

These ground breakages generally coincided with the major axis of meizoseismal area. Right-lateral strike-slip was indicated by en echelon fractures at many locations. Rows of trees (Fig. 7 and 8), pavements (Fig. 9-11), property walls (Fig. 12-13), highways, underground pipe lines (canals) (Fig. 14-15), and roads acrossing the ground breakages were all off-set in right lateral sense. The slippages ranged from tens centimeters to 1.53m horizontally, and at some places were accompanied with vertical displacements about 0.5-0.8m in maximum. Generally, the southeast fault block was dropped down relative to the adjacent nortnwest fault block. The greatest slippage occurred in the middle part of the ground breakages near Jixiang Road, and gradually decreased in both directions. Although the greatest horizontal slippage was 1.53m on the ground surface, the amount of slippages in space varied greatly in a short distance. For instance, the off-set of a water pipe located 40 cm under the ground surface along Jixiang Road was only 40 cm horizontally (Fig. 16). The feature of en echelon fissures appeared as V-shape along their depth (Fig.17) on Jixiang Road, and disappeared at about 2.3m in depth. It may be doubtful if the off-set of the causative fault was through to the surface (overburden).

In addition to off-set and fractures mentioned above, conspicuous horizontal ground deformations without fractures were also observed at some places along the ground breakages (Fig. 18).

Moreover, pavements, rows of trees and corns were off-set horizontally by right-lateral strike-slip of ground fissures in Zhaotan (Fig. 19) and Wanggezhuang (Fig. 20) of Laoting County. The strikes and maximum horizontal displacements were N40°W and 0.8m in the former case, and N50°W and 1.5m in the latter. Both villages were approximately 70km from Tangshan City, and were located in the area of intensity VII. According to the investigation of Exploration Company, Ministry of Metallurgical Industry, these ground fissures were in accordance with the trend of old channels.

3. Damage to Structures and Its Distribution

The maximum intensity (basic intensity) expected before the Tangshan earthquake in Tangshan area was only as low as VI on the Chinese Intensity Scale which is similar to the Modified Mercalli Intensity Scale. Most buildings and structures in Tangshan were designed without seismic consideration.

In meizoseismal area, more than 90% of brick buildings, nearly 80% of mill buildings and constructions were either totally collapsed or seriously damaged (Fig. 21-24). Almost all brick smokestacks collapsed (Fig. 25-26), and elevated water tanks on brick cylindrical shaft usually collapsed near the ground surface (Fig. 27-28).

In Kailuan Coal Mine, nearly 75% of mine shafts suffered various degrees of damage, subsidence or tilting, but no one collapsed. For example, in Tangshan Coal Mine Branch near the west of Yuegezhuang Road a reinforced concrete cylindrical mine shaft of 12m in diameter and 40m above the ground was broken at the section adjacent to the entrance The upper portion more than 30m high inserted into the lower portion of the shaft, with about 7m in length within the portion. The shaft tilted with an angle of 6°-7° in N60°E direction (Fig. 29-30). But a steel mine shaft not far from there was almost intact (Fig. 31). Circular cracks around the cylindrical shaft wall were observed near the ground surface, and serious damage usually appeared on the shaft wall located on the liquefied soil layer.


Fig. 7

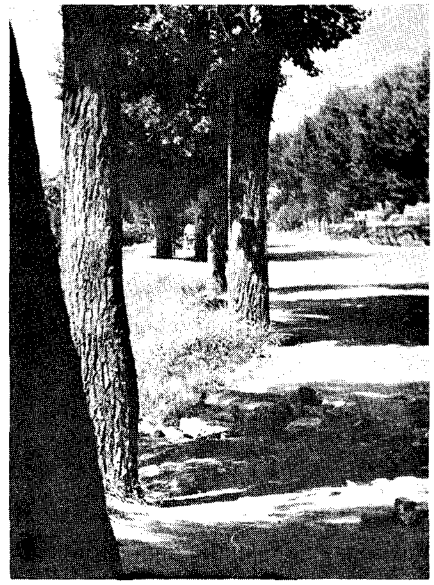


Fig. 8


Fig. 9


Fig. 10


Fig. 11


Fig. 12

Fig. 13

Fig. 14

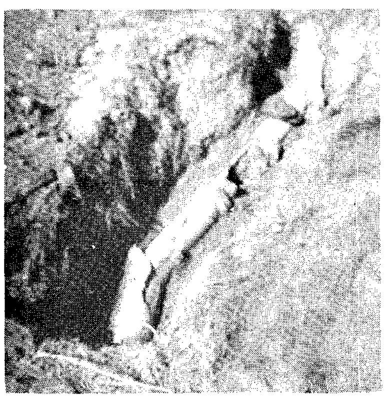


Fig. 15

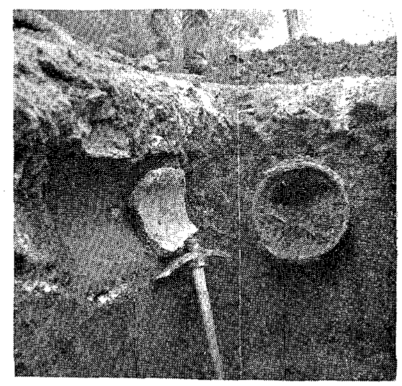


Fig. 16

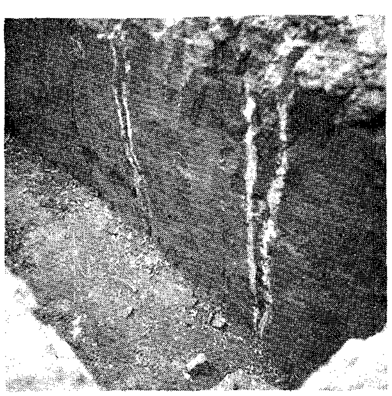


Fig. 17

Fig. 18

Fig. 19

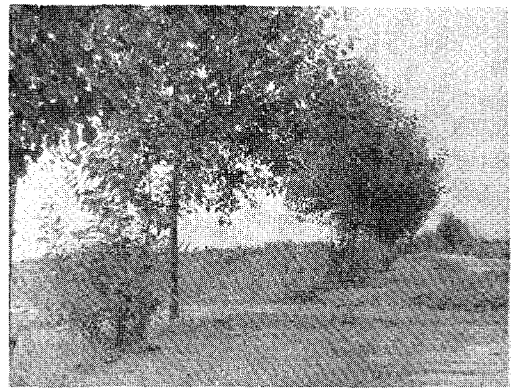


Fig. 20

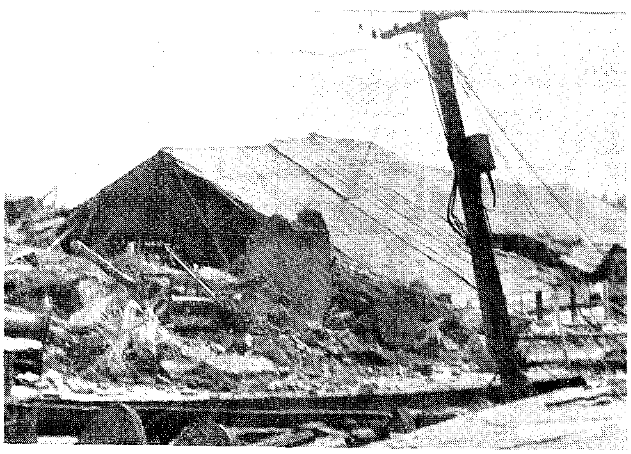


Fig. 21

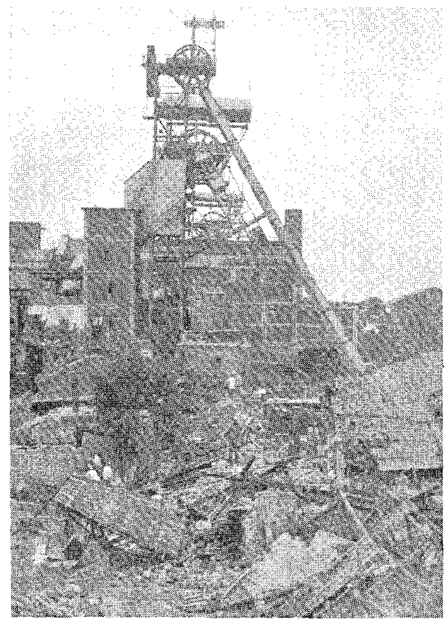


Fig. 22

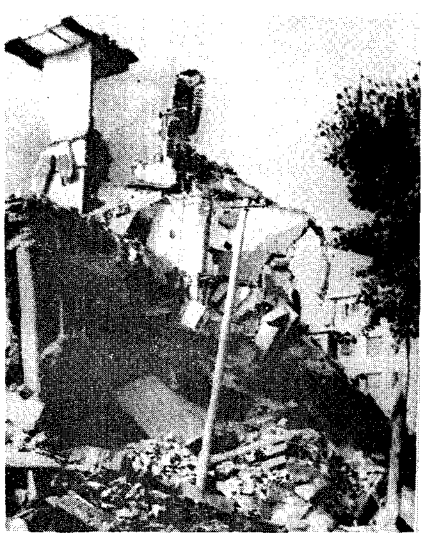


Fig. 23

Fig. 24

Fig. 25

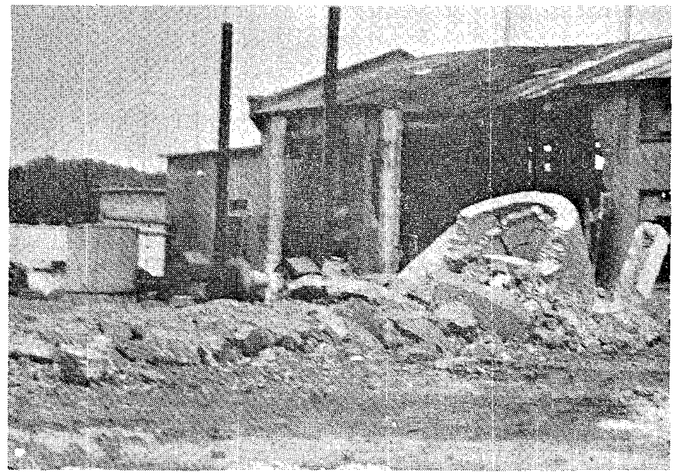


Fig. 26

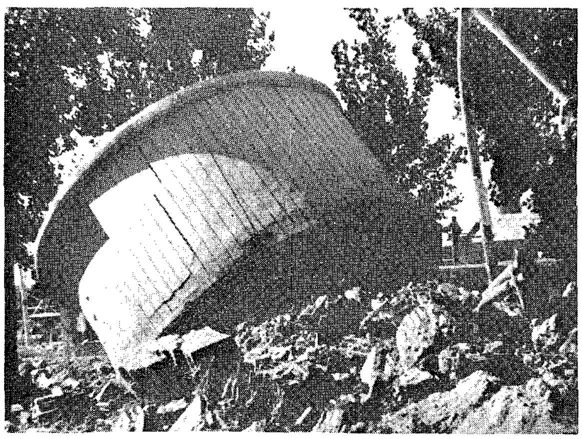


Fig. 27

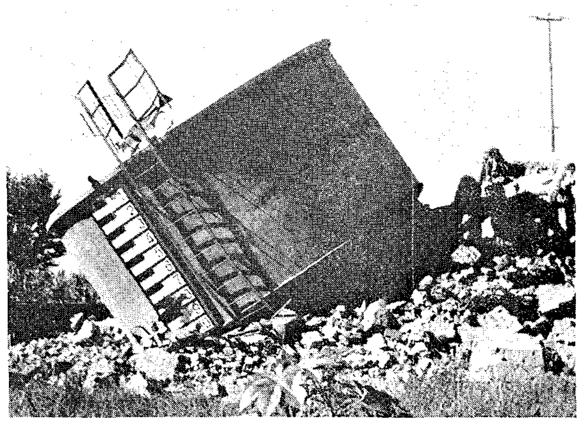


Fig. 28

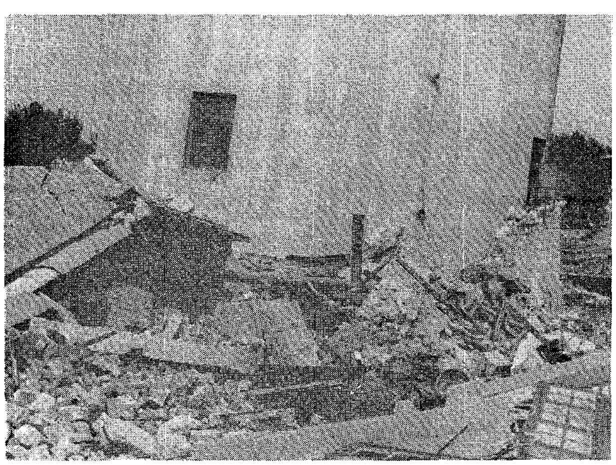


Fig. 29

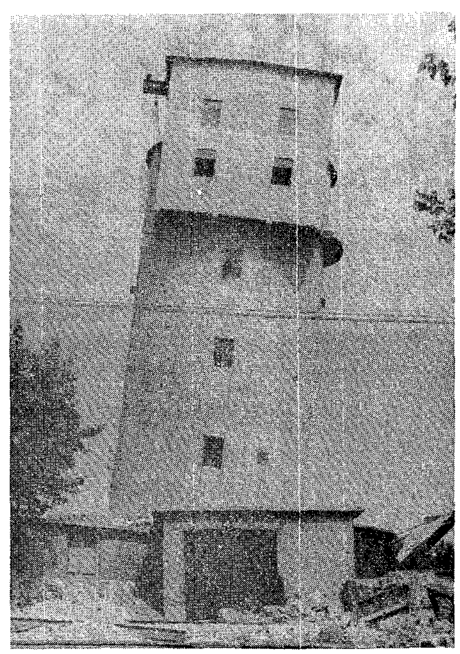


Fig. 30

Most working faces of underground gallery were slightly damaged, only with fissures on arch or debris on ground in a few places. Debris in the seriously damaged east wing of the seventh horizontal transportation gallery of Majiagou Coal Mine Branch were shown in Fig. 32.

The water overflow capacity in the underground galleries of coal mine after earthquake was nearly 2.8 times as much as that before the earthquake, and in Linxi Coal Mine Branch the water flow increased to 5 times as before. Coal mine and equipments in it were all immersed in water, causing secondary damage, and making troubles in reconstruction. Such phenomenon had appeared in some historical earthquakes, too. For example, after the 1945 Luanxian earthquake (Ms=6.7) the water overflow capacity of Tangjiazhuang Coal Mine Branch (epicentral distance Δ =30km) was 1.3 times as before, and after the 1969 Bohai earthquake (Ms=7.4) the water overflow capacity of Tangshan Coal Mine Branch ($\Delta \approx$240km) was 1.1 times as before.

There were many excavated hollow zones along coal mine branches. Ground fissures and deformations appeared along the boundaries of settling pools (Fig. 33-34). Field observation showed that excavated hollow zones had no obvious effect on the building damage.

The damage to water pipe line was strongly correlated with the surrounding soil condition. In southern part of Tangshan City, there were in average nearly 4.3 damaged spots per kilometer of pipe line. In Tangshan Coal Mine Branch, a cast iron pipe line laid on overburden of 2-3m thick natural soil on bedrock (200mm of diameter and one kilometer long) was intact, but another steel pipe line (189mm of diameter and less than 500m long) laid on filled land of 3-4m thick was damaged at six spots.

In Tangshan City, all underground tunnels and basements of buildings were almost intact, except those along the banks of the Dou River suffered serious damage. Fissures occurred only at corners of the cross-section or bends of the tunnels (Fig. 35-36).

Five railway bridges on rather stiff clay located in meizoseismal area suffered slight damage where the intensity rating reached X and XI, while those located on silty clay and silty-sandy clay were seriously damaged, such as Ji Channel Bridge (Fig. 37), Dou River Bridge on Tang-Zun line (Fig. 38). Field observation showed that damage to culverts of various sizes was rather slight. A reinforced concrete culvert with two cavities in Tangshan City was intact.

Along the railway from Tanggu to Fengnan County, there were 106 locations of rail-bend (Fig. 39-40) in a total length of 152km, and nearly 13km long of rail was replaced. Rail-bends occurred in the area of intensity VII or higher, and was remarkably correlated with the residual deformation of railway bed. No correlation can be established between number of railbend and intensity ratings.

There were 28 trains passing in the destructive area when the main shock occurred. Seven of them (two carriages and five freight trains) were overturned or derailed (Fig. 41-42), individual locomotives were set on fire.

Various degrees of highway bridge damage observed in the meizoseismal area (Fig. 43-44) were also apparently correlated with the soil conditions. Shengli Bridge (66m long) was shortened by 2.6 m due to the sliding and tilting of the abutments and river banks, and was seriously damaged, but the deck of the bridge remained on the piers, it fell into the river during the main aftershock.

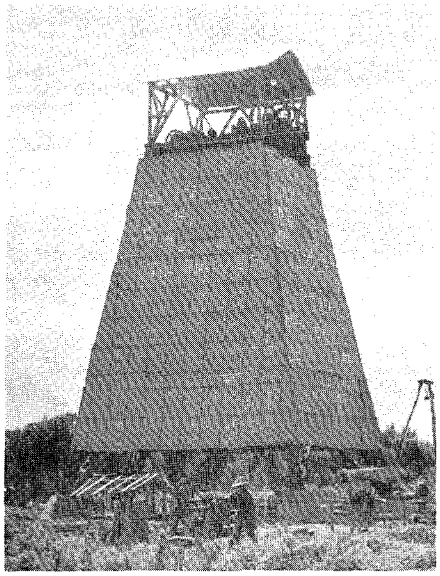


Fig. 31

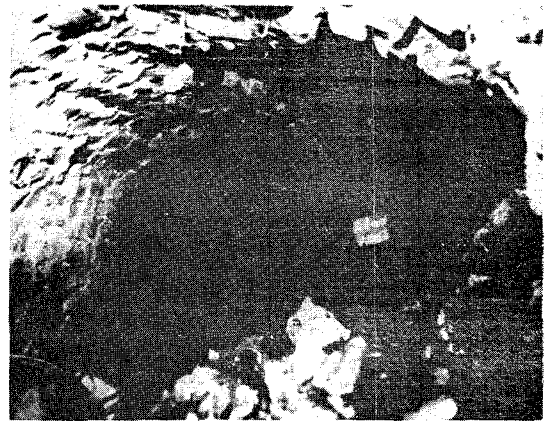


Fig. 32

Fig. 33

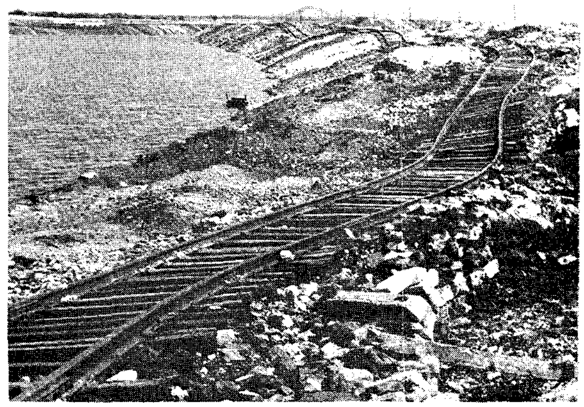


Fig. 34

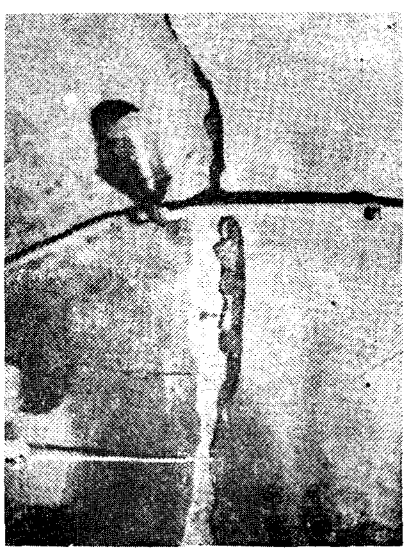


Fig. 35

Fig. 36

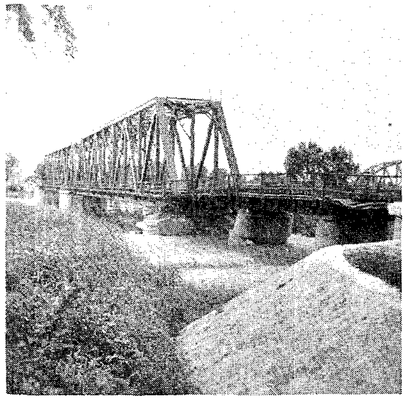
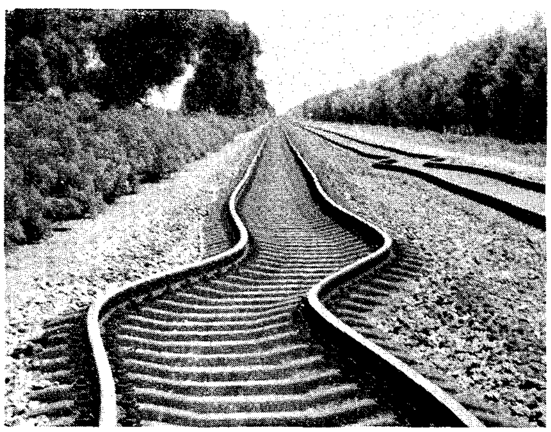


Fig. 37

Fig. 38



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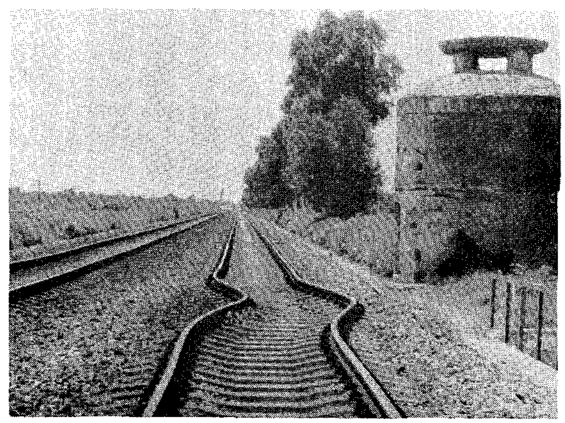

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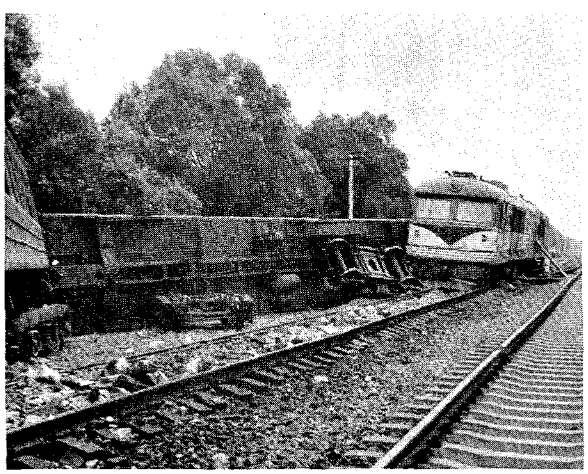


Fig. 41

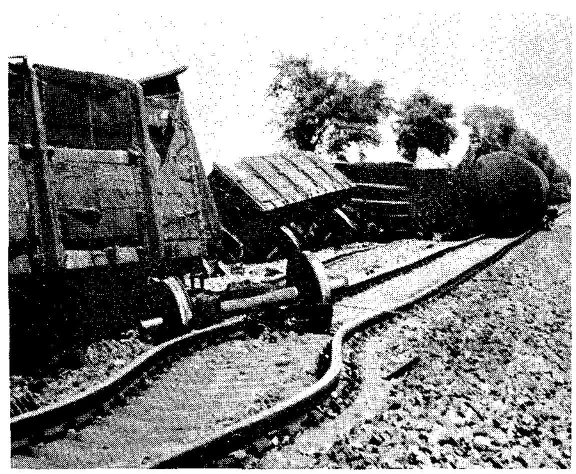


Fig. 42

Sand blows covered an area of more than 24,000 km^2, and nearly 3,000 km^2 of which were serious in amount of sand blowing. Sands blown from underground blocked irrigation canals, water wells etc., and buried a lot of cultivated fields (Fig. 45-46). In the meizoseismal area, sand blows occurred only along the Dou River near the Shengli Bridge, but were not so serious as those in the wide coastal region.

A strange thing happened in cultivated field about 1 km southwest of Luanxian County, that a great amount (more than five carts) of gravel fillet spouted out together with sand, water and some concrete lining from underground through an abandoned well, and formed a 15m radius of gravel cone with a water pit of 3m diameter in the middle. The average diameter of blown gravel fillet is 2-5cm, and the largest one is nearly 15cm. Generally, such gravel fillet was found about 5m under the ground surface, and the underground water table was about 2m below surface. In Qianjiaochang near the west of Luanxian County, some bricks (40cm long) of the wall of an abandoned well spouted out together with white sands, gravel fillet and water from the well, and blocked the well.

An elliptical depression pit suddenly formed (Fig. 47-48) in the afternoon of July 31, in Renxintun near Jinggezhuang Coal Mine Branch. It had a diameter of more than 30m, and more than 10m in depth.

Buildings near the three hills in the northern part of meizoseismal area were not damaged so seriously as those located at the other part of the city, because thin overburden and outcrops of bedrock in the hills played an important role. For example, the intensity ratings of several factories located at the piedmont of Dachengshan hill were only VII-VIII, but the intensity rating of another factory several hundred meters to the north was as much as X.

In meizoseismal area there were still a few buildings near the ground breakages not seriously damaged (Fig. 49-50). A 60m high microwaves tower on good foundation not far from ground breakage was almost intact except that three of the four receivers fell down (Fig. 51), perhapse due to difference in vibrational periods of the steel tower and the ground.

Field observation of damaged multistory brick buildings was carried out door to door by the Hebei Building Design Institute et al. The degrees of damage to multistory brick buildings were divided into seven categories as follows:

(1) Totally collapsed (damage index i_1=1.0) —— The building was totally collapsed or demolished.

(2) Partially collapsed (i_2=0.90) —— The building was partially collapsed or whole piece of external wall collapsed, and the remainders were broken seriously.

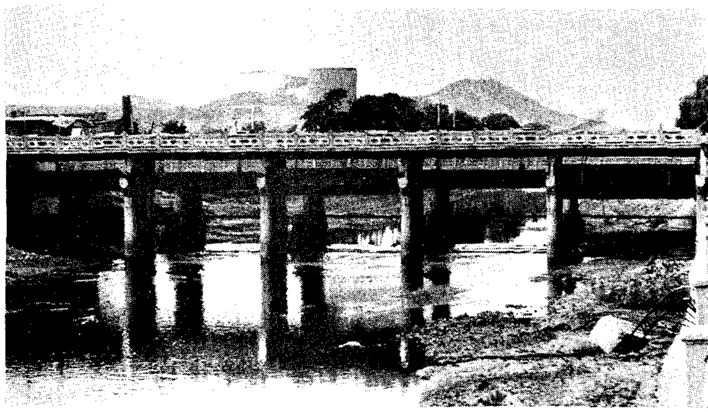
(3) Seriously damaged (i_3=0.7) —— Structural members of building were fractured seriously, and beyond repair.

(4) Moderately damaged (i_4=0.5) —— Cracks appeared in the structural elements of building which still can be used after repairing or strenghtening.

(5) Slightly damaged (i_5=0.3) ——Fissures appeared in the structural elements of building which can be used after repairing.

(6) Nearly intact (i_6=0.1) —— A few fissures appeared in the structural elements of building which can be used safely without repair.

(7) Intact (i_7=0).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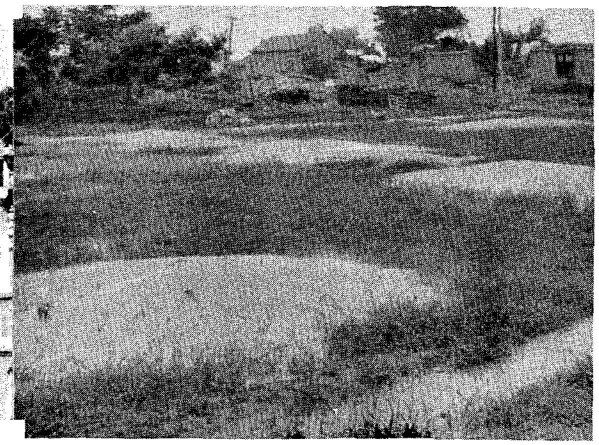
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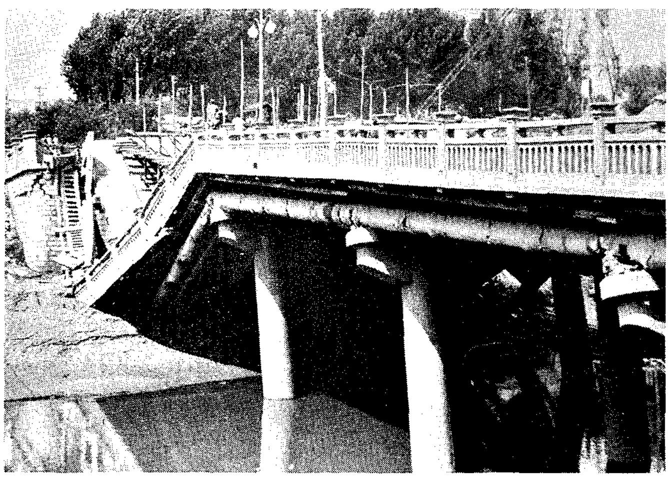
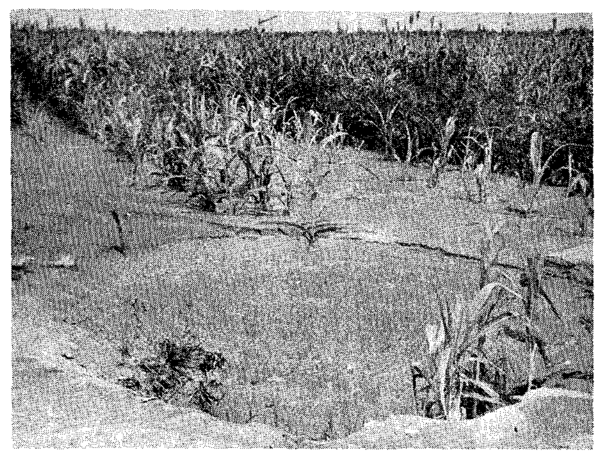


Fig. 44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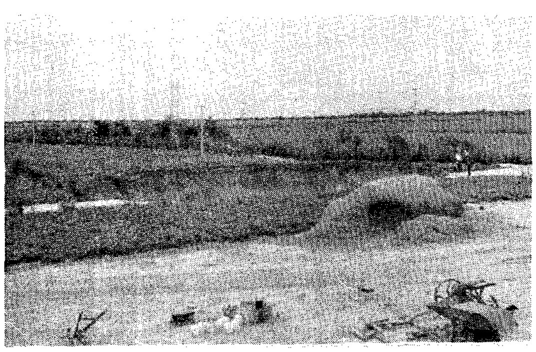


Fig. 47

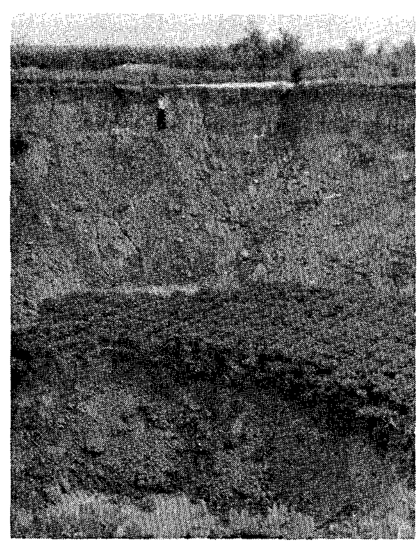
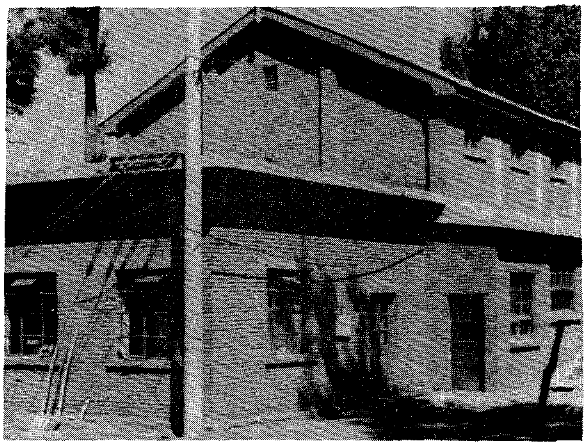
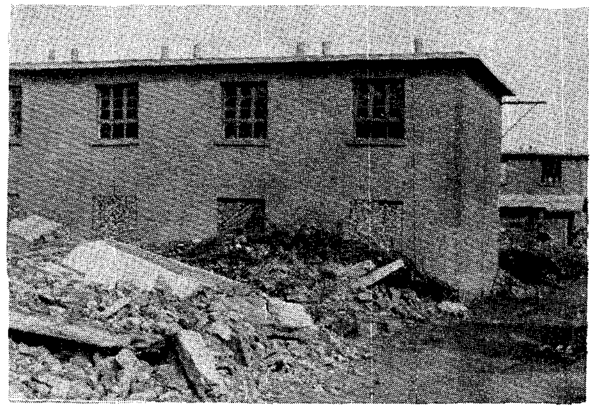


Fig. 48





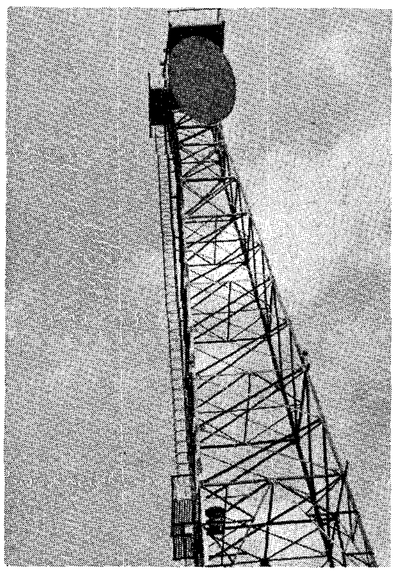
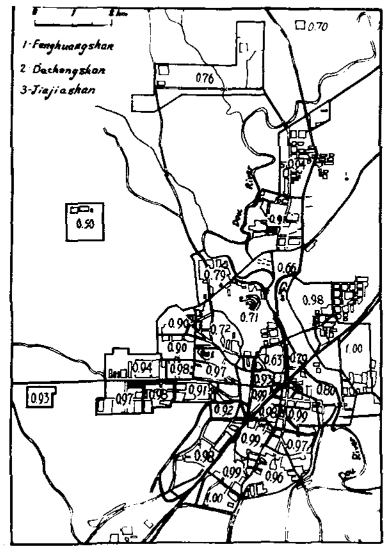
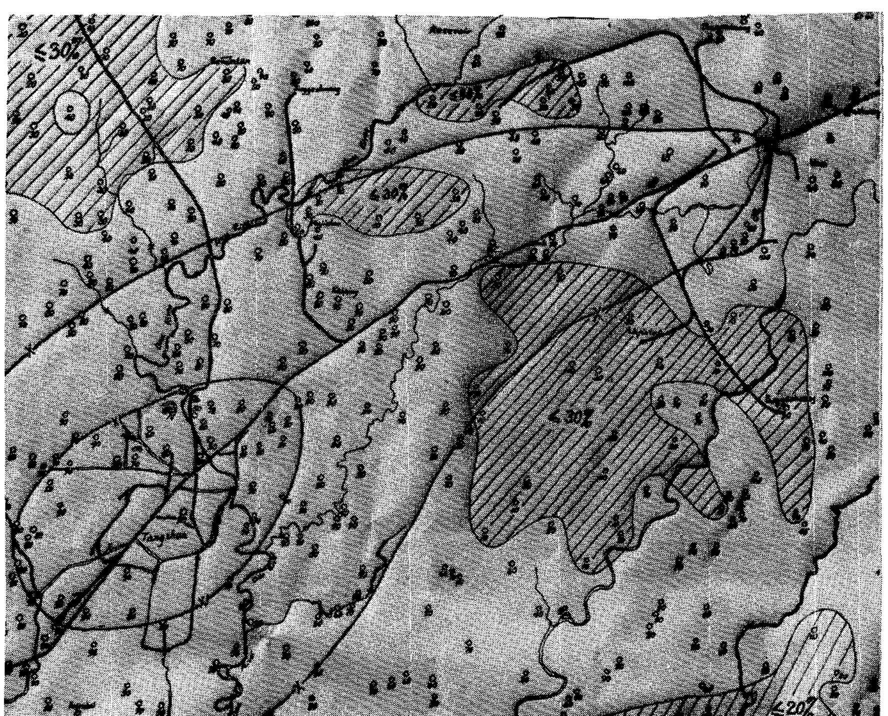


Fig. 49 | Fig. 50

Fig. 51 | | Fig. 52

Fig. 53





Average damage index ($\overline{I}$) was used as an indication of degree of damage to multistory brick buildings in a specified area as follows:

$$\overline{I} = \frac{\sum_{j=1}^{7} i_j n_j}{\sum_{j=1}^{7} n_j}$$

where n_j —— number of multistory brick buildings of damage index i_j within the area. The distribution of average damage index of multistory brick buildings in Tangshan City was shown in Fig. 52.

It can be seen from this figure that, around the three hills and along the banks of Dou River, multistory brick buildings suffered less damage as compared with the other part of the city. In Tangshan City, distance to causative fault didn't play an important role in damage. It is regretted that multistory brick buildings only located in a limited area in Tangshan City, so it is difficult to find out why minor damage to multistory brick buildings occurred along Dou River banks in Tangshan City.

Fig. 53 shows the distribution of the totally collapsed buildings, in percentage, in meizoseismal area and its vicinity, a result from aerial photographs. It seems that the percentages of totally collapsed buildings along Dou River varied with geological conditions. Those buildings slightly damaged were located near the three hills and Douhe Reservoir where the overburden is rather thin, and those seriously damaged were located in the southern part of Tangshan Region. It is interesting to note that the percentage of totally collapsed buildings doesn't decrease gradually as the distance to causative fault increases, and in some places may vary considerably in a short distance; to the east of Tangshan City, several kilometers from the ground breakage, there were some areas of low anomaly.

4. Conclusion

(1) Damage caused by ground failure, such as sand blow, ground crack, rail-bend, damage of underground pipe-line and bridge etc., is more closely correlated with the surrounding site condition than with intensity rating, and is therefore not fit to be an indication of macroscopic intensity.

(2) Outcrops of bedrock and thin overburden site are of benefit for earthquake resistance.

(3) Damage in meizoseismal area and its vicinity varied considerably, and distance to causative fault doesn't play an obvious influence there.

(4) In meizoseismal area, the structures on the ground suffered serious damage, but underground structure, including the basement of building were slightly damaged.

EARTHQUAKE DAMAGE TO PIPELINES

by

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In recent years, several major earthquakes have occurred in China that caused serious damage to pipelines transporting industrial water, domestic water, municipal sewage, and gas. Because of the importance of these pipelines to daily life and the difficulties of rehabilitation, the damage was of great concern to the public. This paper describes and compares the damage caused by the Haichen earthquake (M=7.3) of February 4, 1975 and the Tangshan earthquake (M=7.8) of July 28, 1976. It also summarizes the results of pipeline joint tests conducted in our laboratory and suggests measures of mitigating earthquake damage.

Intensity of the Haichen earthquake was IX on the Chinese Intensity Scale (presented in the Appendix); in Yinkou it was VIII, and in Panjin and Amshan VII. Intensity of the Tangshan earthquake was X-XI; in the urban area of Tianjin it was VII-VIII, and in the suburbs of Tanggu VIII and Hangu IX. In all these localities, water supply, sewage, and gas pipelines were damaged.

1. Water Supply Pipelines

A variety of materials and types of joints were utilized; consequently, different modes of damage were observed such as rupture of pipe barrels, longitudinal cracks, and separation and loosening of joints. Damage to valves and accessories was general; these were also constructed of a variety of materials.

Effect of ground conditions and earthquake intensity on damage

Pipeline damage was affected both by ground conditions and intensities, with ground conditions more critical. During the Haichen earthquake, intensities at both Anshan and Panjin were VII, but the damage rate of cast iron pipe pipe in Anshan was 0.08 No/km* due to its better foundation; and that in Panjin was 0.8 No/km owing to its high ground water table and sand layer liquefaction.

During the Tangshan earthquake, intensity in the urban area of Tianjin was VII-VIII with a class 3 ground condition**, and the corresponding damage rate was 0.18 No/km. Intensity in the Tanggu area was VIII with a class 3 ground condition also but worse geological conditions; the damage rate was 4.18 No/km. The intensity in the Hangu area was IX with a class 3 ground condition of silt-like soil and a high water table; the damage rate was 10 No/km. Intensity at Tangshan was X-XI with a class 2 ground condition; the damage rate was 4.0 No/km. As shown in Table 1, the ground condition is of primary importance. Note the anomalous behavior indicated in Table 1.

It is also clear that different foundations lead to different types of failure. The percentage of ruptured pipe barrels in Tangshan was 20.4%; on the other hand, in Tianjin, where the soil is very soft and deforms greatly under seismic motion, the percentage of rupture was 45%.

* Number of breaks per kilometer.

** Class 1 soils (rock)
Class 2 soils (firm, stable)
Class 3 soils (soft, miscellaneous)

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TABLE 1. RELATIONSHIP OF CAST IRON PIPE DAMAGE
TO EARTHQUAKE INTENSITY AND GROUND CONDITION

Locality	Intensity	Ground Condition	Damage Rate (No/km)	Remarks
Tianjin	VII-VIII	Class 3	0.18	
Tanggu	VIII	Class 3	4.18	Worse geological condition than Tianjin
Hangu	IX	Class 3	10.00	Worse geological condition than Tanggu
Tangshan	X-XI	Class 2	4.00	

Effect of geography and terrain on damage

All pipelines along or across rivers and streams were severely damaged. Some banks slid; some moved into the river beds. Hence the pipes were pulled out of the joints. During the Haichen earthquake, both pipelines crossing the Liao River cracked. In the Tangshan earthquake, all six pipelines crossing the Dou River sustained burst joints; a gauge well was displaced 40 cm; and a portion of pipeline along the Dou River was pulled up toward the stream as much as 2.5 meters. In Tianjin, two pipelines across the Hai River were damaged. In Tangshan, hollow zones were excavated by mining, and most of the cast iron pipelines through these areas were badly damaged, with linear breaks, pulling out or shearing off at joints, etc. Some vertical faults in joints reached 50 cm, and horizontally the joints could be pulled away from each other 7-8 cm. Faults in steel pipes occurred, and some threads tore off. In locations of land fill, ponds, slope, and uneven surfaces, the damage was also significant.

Effect of materials on damage

In China, steel, cast iron, prestressed reinforced concrete, self-stressed concrete, asbestos-cement, and some polyvinyl chloride pipes are used for water supply. The steel pipes have high tensile strength and good ductility. In Tianjin, submerged steel pipes across the river were unaffected, but cast iron pipes under water leading to the shore were damaged. Corrosion of steel pipes is most apt to occur if anti-corrosion is not properly provided. Thus, in Tangshan, where many steel pipelines were laid many years ago and some of the insulating layer had worn out, the damage rate of 150 mm steel pipelines 500 meters long even reached a value of 6.67 No/km.

At present, the quality of cast iron pipes in China is not so good and hence had the highest rate of damage. The better quality pipes are prestressed reinforced concrete or self-stressed concrete. There are many applications in the cities involved. A 600 mm diameter, 19.5 km long prestressed concrete pipeline in Yinkow and a 600 mm diameter, 5.6 km long prestressed concrete pipeline in Tianjin worked perfectly after the earthquakes. Similarly, a 500 mm diameter self-stressed concrete pipeline in Tangshan remained in good condition, with only a few joints loosened by the shaking.

In the Haichen earthquake, all asbestos-cement pipes jointed by cast iron flanges and rubber ring connections remained intact. Asbestos-cement pipe is somewhat brittle and may fail if rigid joints are used. Polyvinyl chloride pipe is also brittle and has a greater slenderness ratio due to its relatively small diameter. A great many failures of this type of pipe were found in Tianjin.

Pipe joint key to earthquake resistance

In general, Portland cement mortar, self-stressed cement mortar, or asbestos-cement is used as the joint staff for cast iron pipes. These form a kind of rigid joint which when subjected to loading has a linear stress-strain relation and a longitudinal elongation commonly equal to or less than 0.06 mm. The deflection angle of such joints is also small. Tests have shown that their deflection angle is in the range of 0°08' to 0°19'; therefore, many joints of this type became water-infiltrating, water-leaking, or were pulled away or even crushed. The joints of prestressed reinforced concrete and self-stressed concrete pipes are of the socket type with rubber rings. This kind of joint is flexible and capable of elongation; when subjected to loading, the compressed rubber ring acts in friction. When the pipe is elongated and bending, the water pressure is balanced by the frictional force between the rubber ring and the pipe wall, forming a critical condition for leakproofing. The longitudinal elongation of this kind of joint may be 12 mm, and the deflection angle may be 2°06'. For an asbestos-cement pipe joint with flanged collar and rubber ring, the longitudinal elongation may be 20-28 mm, and the deflection angle 9°02' so as to withstand adverse effects of external forces. At the same time, rigid collar joints sustain serious damage. In the same Tanggu area, asbestos-cement pipelines with flanged collar rubber ring joints had no failure, but those with rigid joints exhibited a damage rate of 16 No/km.

Effect of pipeline diameter on damage rate

In both the Haichen and the Tangshan earthquakes, the damage rate varied inversely to the pipeline diameter. It was obvious that the smaller pipes were more liable to break (see Table 2).

TABLE 2. EFFECT OF PIPELINE DIAMETER ON DAMAGE

Locality	Pipe Diameter (mm)	Damage Rate (No/km)
Yinkou	100	1.8
	150	0.88
	300	0.13
Tianjin urban area	50	1.13
	75-600	0.20
	600	0.04
Tangshan	150	5.23
	300	4.63
	600	1.89

From the variation of pipeline damage in different localities, it can be seen that the damage rate decreases as the pipe diameter increases. Under the seismic wave action, there is a relative deformation between the pipeline and the ground. The pipeline deforms as the surrounding soil deforms, and the magnitude of deformation is related to the rigidity of the pipe itself. While the pipe diameter increases, the rigidity and the resistance to deformation increases, the relative deformation becomes more significant, and the actual pipe deformation diminishes; meanwhile, the damage rate decreases correspondingly.

Pipe fitting connections more apt to suffer damage

Pipe fitting connections which change direction or diameter have obvious mass differences which cause local stress concentration and lead to breaks in the pipeline. In Tianjin, the failures in tee, cross, and elbow joints amounted to 23% of the total damage to pipelines; in Tanggu, these types of failure amounted to 18.5% of the total. In Tangshan, there were also many instances of breaks and faults in tee and elbow joints, and of disruptions in gauge well flanges.

2. Gas Pipelines

During the Haichen earthquake, part of the underground steel gas pipeline suffered cracks in welded joints. The damage rate was 0.31 No/km for 530 mm diameter pipe and 1.6 No/km for 50-100 mm diameter pipe. Another part, made of 150-300 mm cast iron pipe jointed by cement mortar, was severely damaged. In Tangshan and Tianjin, many elevated gas pipelines were disrupted by a nearby building; their welded joints cracked and supports twisted and tilted. At the connections between pipelines and equipment, tee and elbow joints and cast iron flanges often broke as a result of the difference in frequency and direction of vibration.

3. Sewer Pipelines

In Tangshan, the sewers commonly used 700-1500 mm diameter reinforced concrete pipes and reinforced concrete masonry box culverts up to 2 x 1.7 meters. They suffered much higher damage. The pipe joints were mostly of cement mortar, and the earthquake damage generally consisted of dropped mortar and parted joints. Box culverts failed mainly by splitting and tilting walls. In Tianjin, some of the joints were made of asphalt felt; they often pulled apart. In Changde Road, Tianjin, a 4.5 x 3 meter egg-shaped concrete pipe broke, and a large quantity of soil scoured into the pipe, resulting in ground settlement and severe settling of nearby civilian buildings.

4. Earthquake-Resistant Joint Experiment

This work is still in the beginning stage. However, some pipe joint tests were conducted for it was felt that joints are the key to earthquake resistance. Many basic experiments for existing joint types were considered, such as determination of elongation value, deflection angle, and so on. As a result of this analysis, we believe it is necessary to redesign a joint that will meet the requirement of seismic-resisting structures. Recently, a cast iron pipe joint with wedge-shaped rubber ring was developed; tests showed the deflection angle can be 7° and the axial elongation 16-27 mm, which fulfills the seismic-resistance requirement. The experiment used a QZJ-1 exciter to place the pipe joint under reciprocating axial tension. Test results are summarized in Table 3.

The shape of the joint and physical properties of its wedge-shaped rubber ring have determined that it should be both leakproof and anti-seismic. The test results all exceeded the calculated values, as shown in Table 4.

TABLE 3. RESULTS OF EARTHQUAKE-RESISTING JOINT EXPERIMENT

Internal Water Pressure (kg/cm^2)	Static Elongation (mm)	Vibration Test		Total Elongation (mm)	Remarks
		Frequency (Hz)	Axial Elongation (mm)		
0	20	2.3	4.0	20±4	No infiltration
2.5	20	2.17	5.0	20±5	No leakage
5.0	20	2.0	4.0	20±4	
10.0	20	2.3	4.0	20±4	
10.0	20	2.5	6.0	20±6	
10.0	20	3.3	7.5	20±7.5	

TABLE 4. COMPARISON OF CALCULATED AND TESTED AXIAL ELONGATION

Intensity	Axial Elongation (mm)		Remarks
	Calculated	Tested	
VIII	1.59	20±4 to 20±7.5	Assume: V_s = 140 m/sec
IX	3.7	20±4 to 20±7.5	E = 1.1×10^6 kg/cm^2 L = 5.0 meters D = 150 mm

The pipeline design formula used in the calculation is suggested by the public works earthquake resistance design specification, which is based on the summary of experience of the Haichen and Tangshan earthquakes.

The permissible axial elongation of the pipe joint can be determined by the following equation:

$$\sum_{t=1}^{n} [u] \geq 66\,\xi \,.\, K_H \,.\, T_m^2$$

where [u] is permissible axial elongation of pipe joint (mm)

n is number of joints within half a wave length

K_H is horizontal seismic coefficient

and $n = \dfrac{V_s T_m}{\sqrt{2}L}$

where V_s is velocity of transverse waves transmitted in the ground during an earthquake

T_m is ground period (seconds)

L is pipe length (meters)

ξ is transfer coefficient

and $= \dfrac{1}{1 + \dfrac{EFD}{2V_s^2}}$

where E is modulus of elasticity of pipe material (kg/cm^2)

F is cross sectional area of pipe (cm^2)

D is average diameter of pipe (mm)

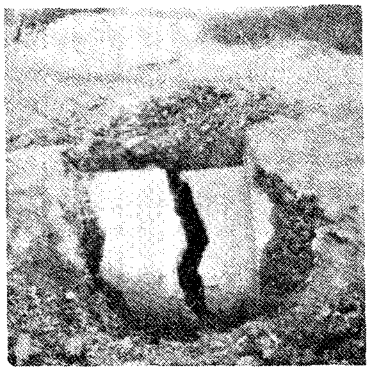
Conclusions

1. Seismic damage to pipelines is related to many factors such as ground conditions, earthquake intensity, geography and terrain, pipe material, type of joint, diameter of pipe, and so on; each should be analyzed separately.

2. To avoid or minimize pipeline damage, attention must be paid to choice of a suitable foundation. Flexible joints should be provided where there are horizontal and vertical turns; boundaries between hard and weak soil; and connections with fittings, machines, or buildings. Supports of elevated pipelines must be designed to resist earthquake shock. Water supply pipelines must be designed to be able to operate after a major earthquake; and pipelines of a gas system must be provided with automatic shutoff devices.

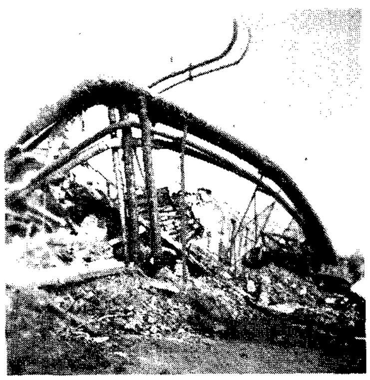
3. The quality of the pipe material and fittings must be in accordance with the seismic resistance requirement. The quality of the cast iron and the steel pipe welding should be improved. The insulation layer must not be neglected. Development of prestressed reinforced concrete pipe is important, for it has better properties for resisting earthquakes.

4. In order to satisy the requirements of municipal water supply and sewage, heat and gas services, chemical engineering works, etc., the study of pipeline earthquake resistance should be expanded to include the following topics: pipeline calculation during seismic motion, pipeline stress on different foundations, types of joints, pipeline materials, establishment of earthquake observation stations in large cities to determine the seismic characteristics of pipelines during earthquakes in order to obtain original data for the purpose of better defined methods of seismic resistance.



1. Pipe body ruptures.

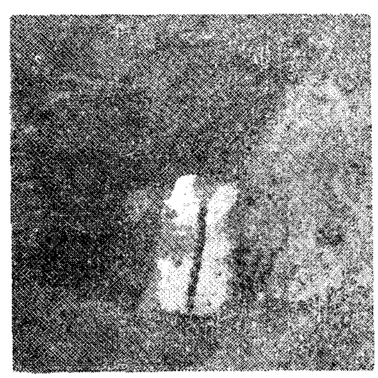
4. Cement mortar drops and sewer pipe joint parts.



2. Elevated gas pipe twists and tilts.

5. Pipeline pulls up toward stream.

3. Cast iron pipe cracks.



6. Pipe joint separates.

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DAMAGE IN TIANJIN DURING TANGSHAN EARTHQUAKE

by

Jin Guoliang*

1. Basic Circumstances of Earthquake

The Tangshan earthquake of July 28, 1976 was world-famous as a strong earthquake, with a magnitude of 7.8. Its epicenter was at Tangshan, and the focal depth ranged from 12 to 16 km. Intensity of the earthquake at the epicenter was XI on the new Chinese Intensity Scale (presented in the Appendix), which is similar to the Modified Mercalli Intensity Scale.

Tianjin was about 100 km from the epicenter. The intensity in the urban area was VIII, while that in the suburbs and affiliated counties varied from VII to IX. Fig. 1 is an isoseismal intensity map of Tianjin, Beijing, and Tangshan. It can be seen that the city of Tianjin was an area of abnormal intensity. The backfill lands and soft soil were accountable for this anomaly.

Tianjin, over 100 km southeast of Beijing, is the third biggest city in China. It was constructed almost 100 years ago and has numerous industrial and other buildings. Most civil buildings are of brick-timber or brick-concrete. Industrial buildings are mostly concrete frame or reinforced concrete single-story structures. There are many brick chimneys in Tianjin factories.

Seismic damage of Tianjin during the Tangshan earthquake may be described in three parts: 1) types of damage, 2) aseismic strengthening measures, and 3) secondary damage.

2. Types of Damage

The Tangshan earthquake caused serious damage to Tianjin. Five principal types of structural damage were noted, as described below.

Damage Due to Foundation and Soil

Sand Liquefaction. Tianjin is located near the sea. The overburden layer, consisting of soft clay and fine sand, is about 1000 meters thick. This accounted for the common phenomena of settlement and sand liquefaction during the quake.

Fig. 2 shows a mill in Hangu that tilted; the columns leaned about 40 cm at the top because of sand liquefaction. Fig. 3 is a water tower in the area of Intensity VII. It leaned about 30 cm — also due to sand liquefaction. Fig. 4 is another water tower in the Intensity VII area which tilted significantly because of sand liquefaction. Oil tanks in Tanggu District fell down because of sand liquefaction, as shown in Fig. 5. Fig. 6 is an observation tower of the Hangu Fire Brigade in an Intensity IX area that tilted due to sand liquefaction.

* Deputy Head of Research Institute on Earthquake Engineering, Tianjin

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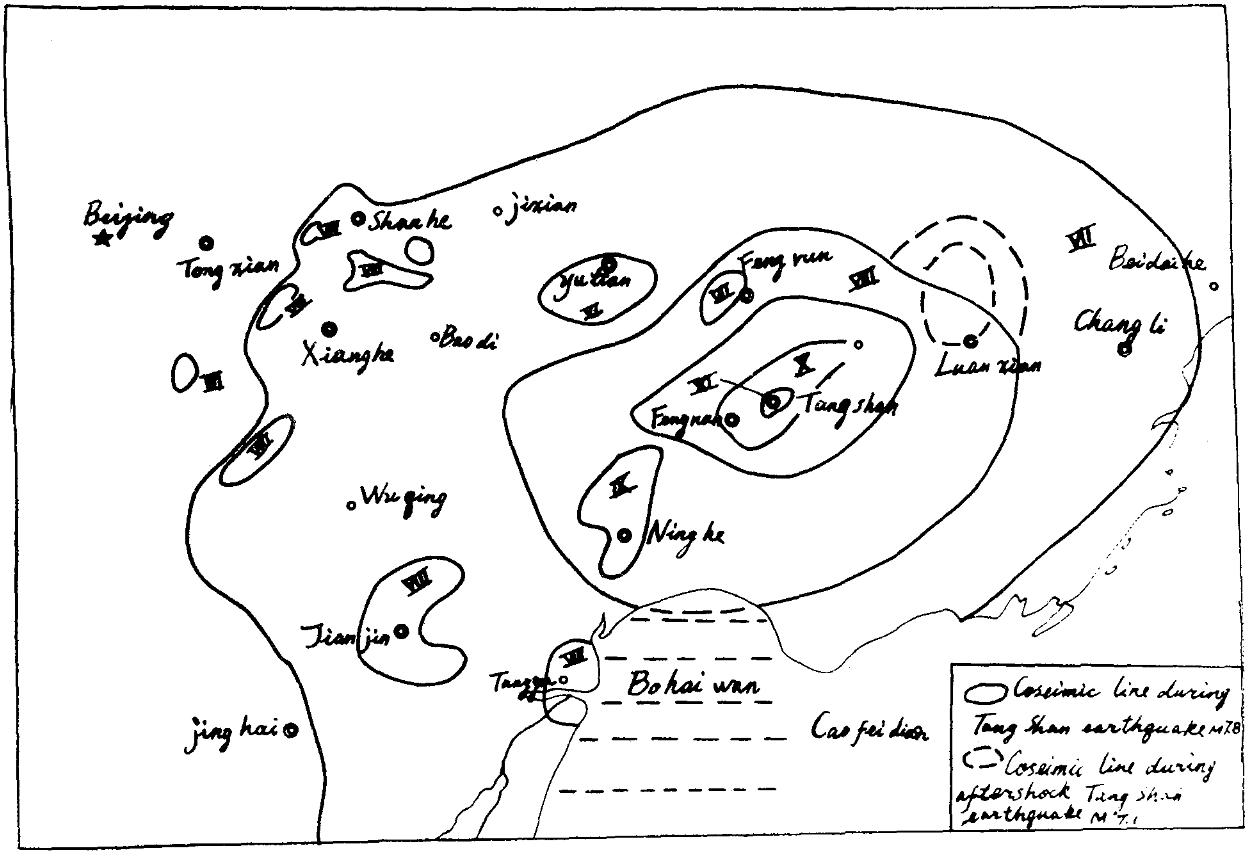


Fig. 1. Isoseismal Intensity Map of Tianjin, Beijing, and Tangshan During Tangshan Earthquake.

Fig. 2. Leaning Mill in Hangu, a Suburban Town.

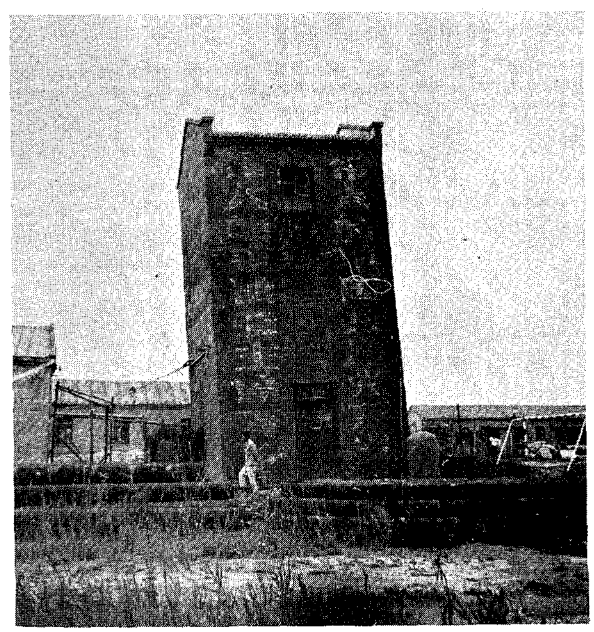


Fig. 3. Leaning Water Tower in Southern Suburb of Tianjin.

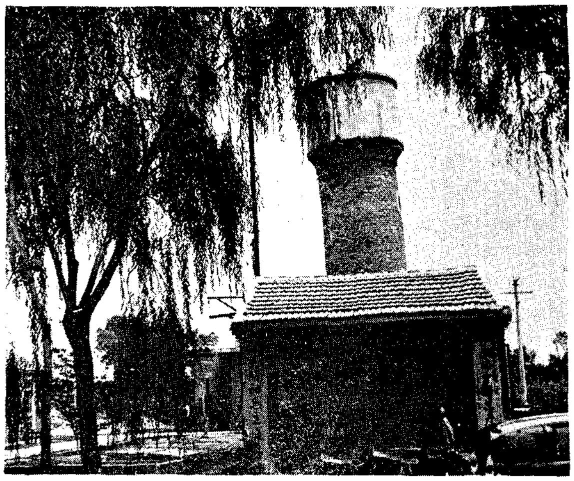


Fig. 4. Leaning Water Tower in Tanggu.

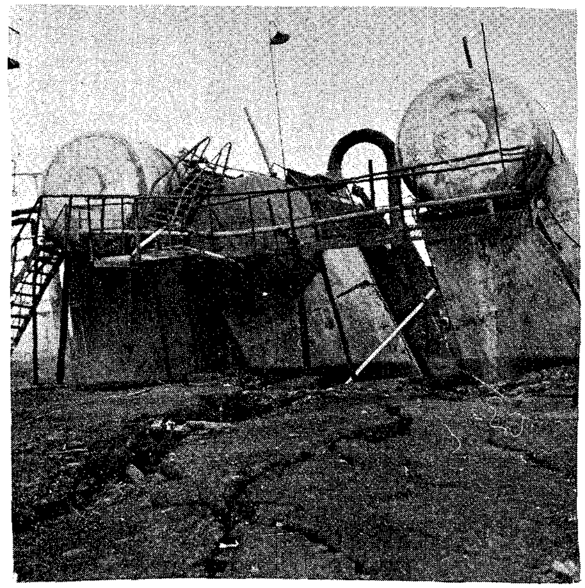


Fig. 5. Collapsed Oil Tanks in Tanggu.

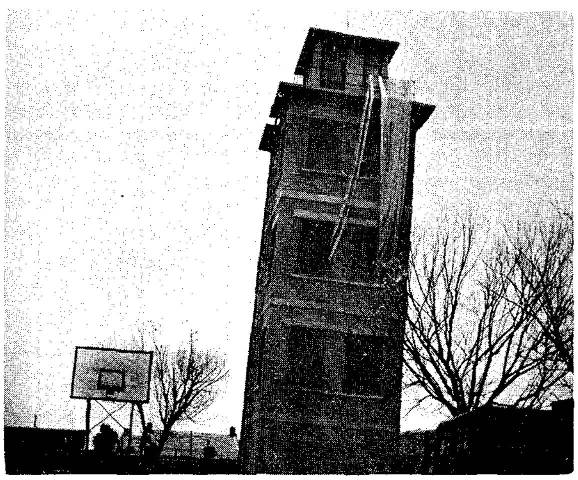


Fig. 6. Tilted Observation Tower of Hangu Fire Brigade.

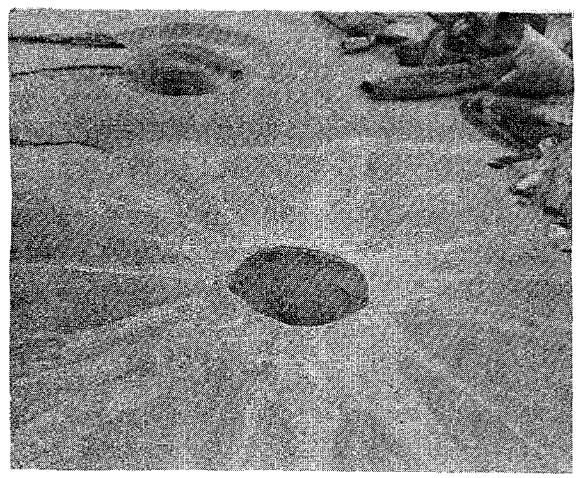


Fig. 7. Sand Blow.

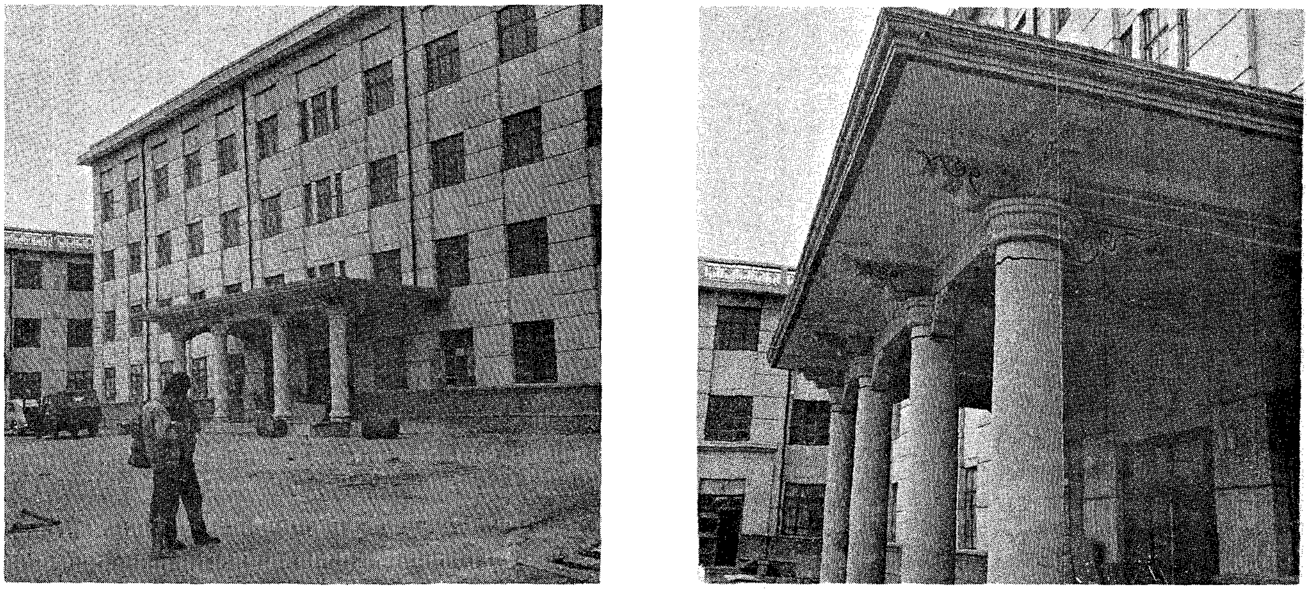


Fig. 8. Four-Story Brick Building Settled, Cracking Canopy Column.

Settlement. Buildings settled significantly because of the soft soil foundation conditions in Tianjin. Fig. 8 shows a four-story brick building in an area of Intensity IX which settled approximately 30 cm during the earthquake; the settlement cracked the canopy column in front of the door.

Ground Cracks. During the earthquake some buildings sustained cracks. Fig. 9 shows a veranda broken by ground cracking; the ground level difference between the two sides of the crack was about 60 cm. A four-story brick building in the residential district broke at the center because of a ground crack beneath it (Fig. 10). Fig. 11 shows the form of development of the crack in Hangu Fu Village.

Fig. 12 shows a mill building's basement in Tanggu. The spread footing distorted due to ground cracks and sand liquefaction before the building was built.

Flow Slides. Many buildings were damaged by numerous ground cracks which occurred simultaneously with flow slides along the two sides of the Haihe River and the seashore. Fig. 13 shows a typical flow slide along the river.

Ground deformation was severe during this earthquake. Fig. 14 shows rails in the area of Intensity IX bent by ground movement. Phenomena like this were commonplace.

Damage to Brick Buildings

In areas of Intensity IX nearly all brick buildings were damaged. A five-story restaurant with concrete floors and brick walls fell down on account of the high intensity of the earthquake and low strength of the brick walls (Fig. 15). Even the reinforced concrete mill buildings did not survive. Fig. 16 shows a fallen mill building whose columns inclined and roof and walls collapsed completely.

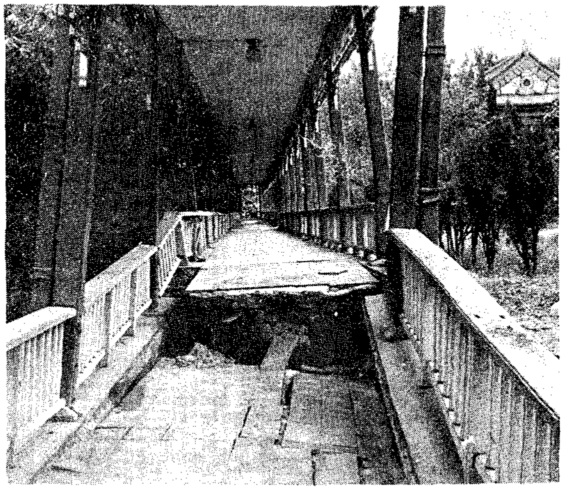


Fig. 9. Cracks in Hospital Veranda.

Fig. 10. Cracks in Four-Story Brick Apartment House.

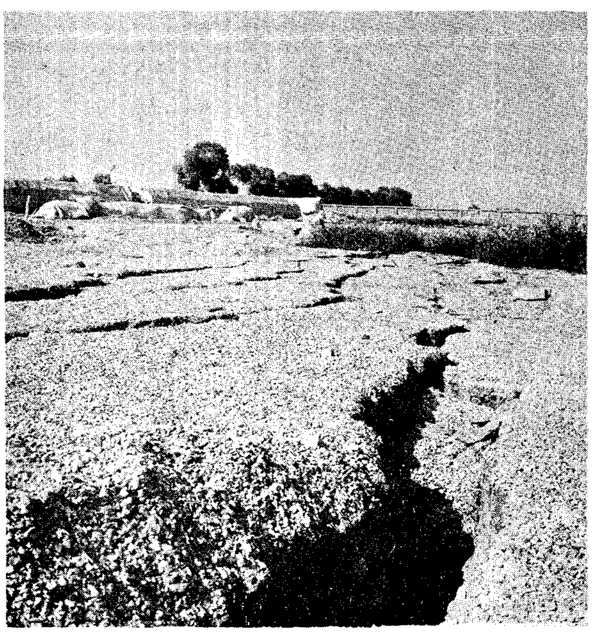


Fig. 11. Parallel Ground Cracks in Hangu Fu Village.

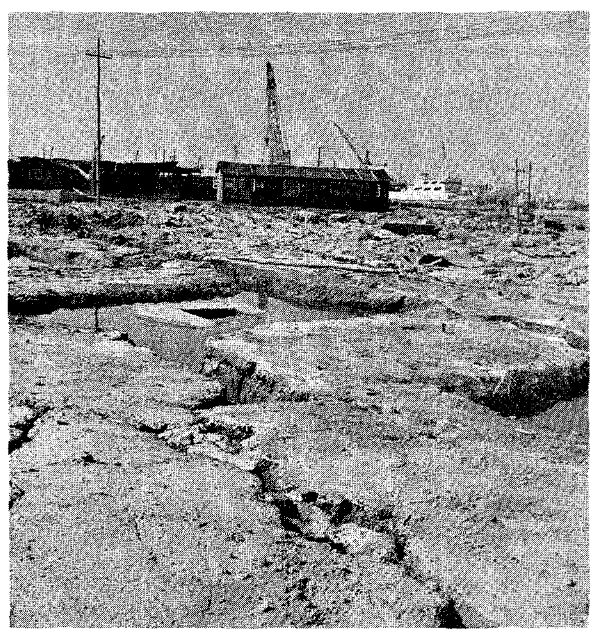


Fig. 12. Distorted Spread Footing of Mill Building in Tanggu.

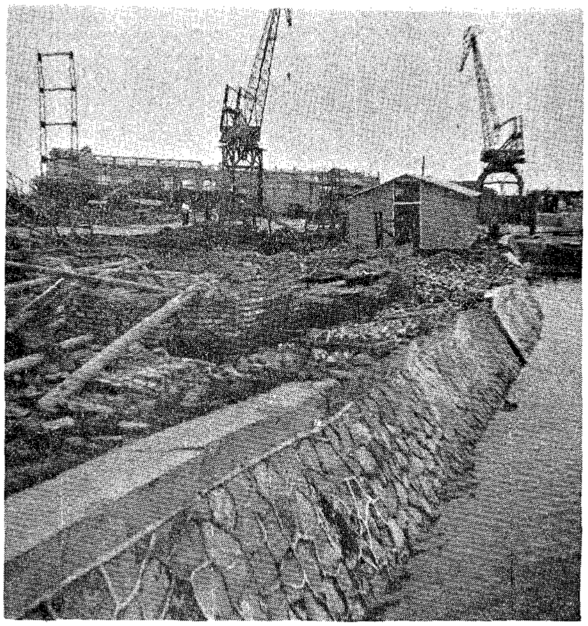


Fig. 13. Flow Slide in Tanggu.

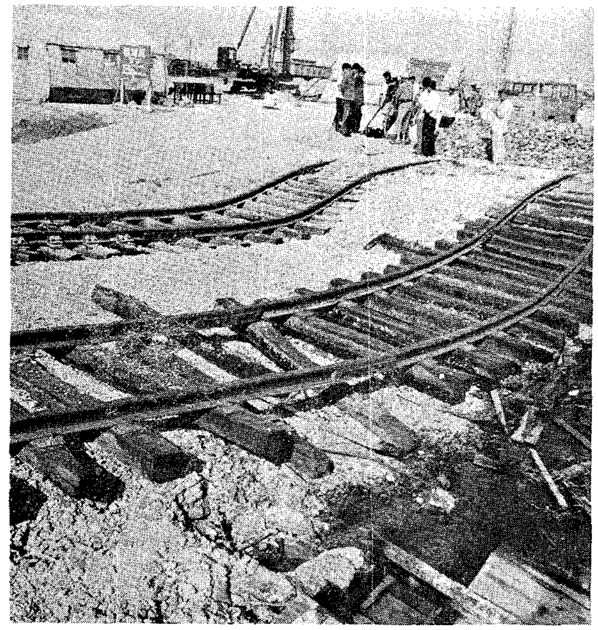


Fig. 14. Curved Rails in Tanggu.

Fig. 15. Collapsed Five-Story Concrete Floor/Brick Wall Restaurant Building.

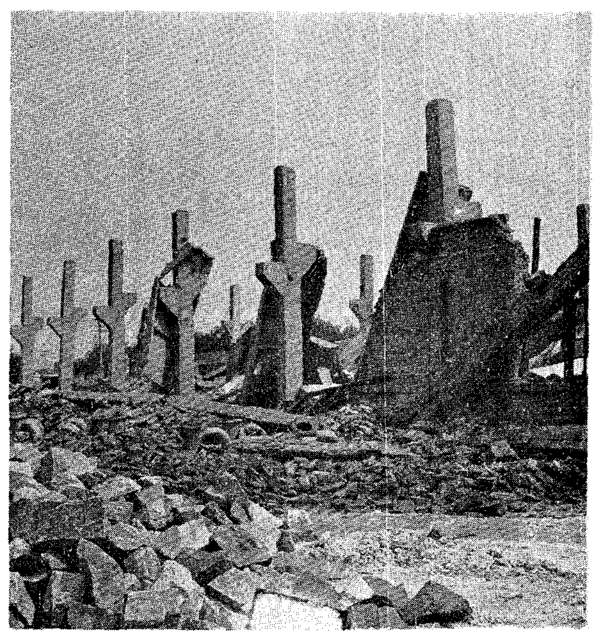


Fig. 16. Collapsed Reinforced Concrete Mill Building, With Tilted Columns, in Hangu.

In Tianjin urban area there were a lot of old brick buildings with mud mortar and wooden floors. Buildings of this type failed completely.

Figs. 17 and 18 show old brick buildings with timber floors severely damaged because connections between wood floors and brick walls were weak, mortar strength low, and the buildings very old. Many such buildings failed completely as a result of tilting or collapse of walls.

In Intensity VIII areas, few newly constructed brick buildings with reinforced concrete floors collapsed, though varying degrees of damage occurred. In most cases, longitudinal and transverse walls were broken by shearing or part of the end walls collapsed. This type of destruction is mainly attributed to low strength mortar and poor workmanship. Figs. 19 and 20 show two buildings damaged by shearing. Fig. 21 is an X-crack in an interior wall.

It was observed that damage was least in brick buildings with larger girths (reinforced concrete beams around the outside of the building).

Many recently built buildings with brick walls and concrete floors survived the earthquake. Fig. 22 shows this type of building. Buildings with large panel structure also behaved well (Fig. 23).

Prefabricated wall boards have good properties. Fig. 24 is a building with prefabricated wall boards. It was not damaged during the earthquake thanks to its light weight and good connections.

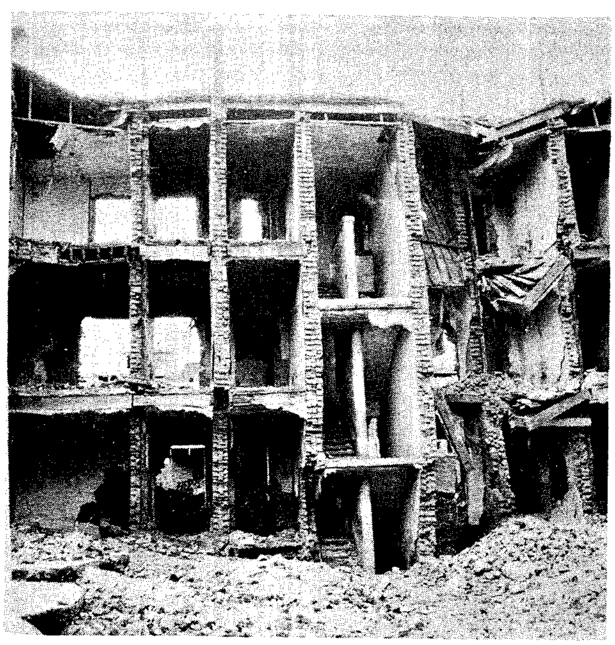


Fig. 17. Partially Collapsed Three-Story Brick Building With Timber Floors.

Fig. 18. Collapsed Facade Wall of Three-Story Brick Building With Timber Floors.

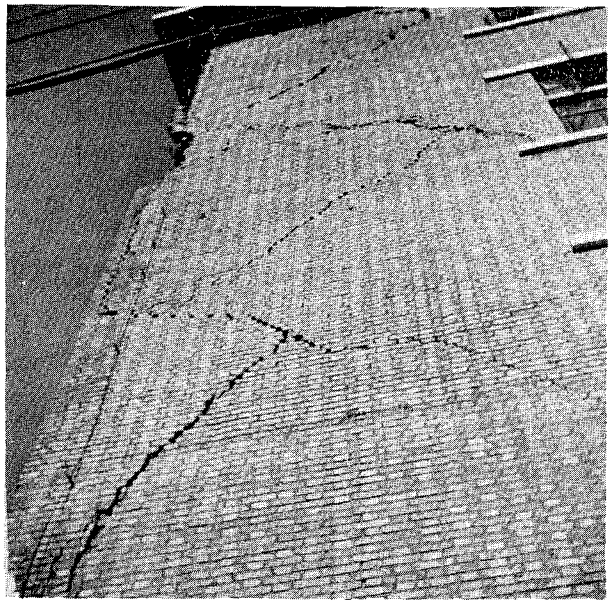


Fig. 19. Shear Damage in Newly Constructed Five-Story Brick Building.

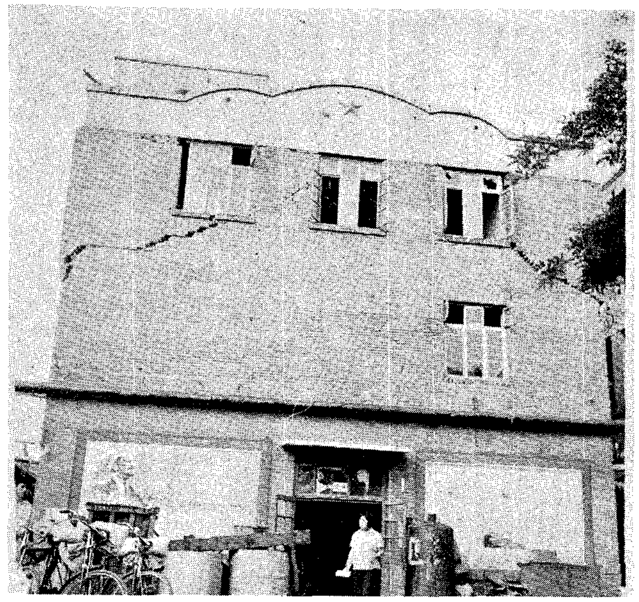


Fig. 20. End Wall Damage in Newly Constructed Three-Story Brick Building.

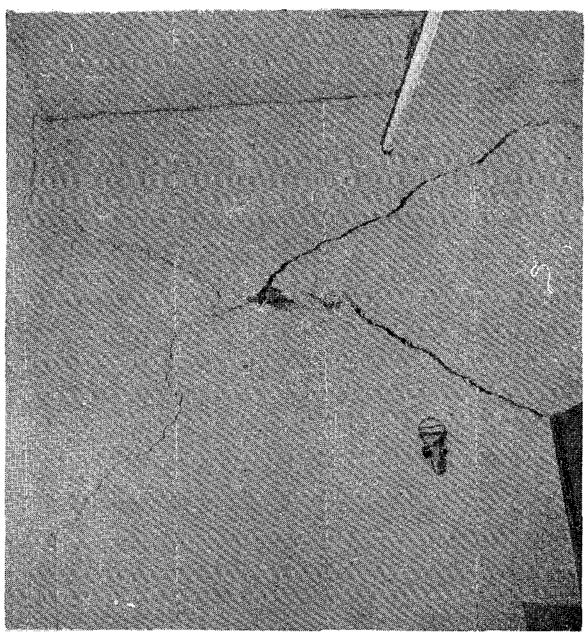


Fig. 21. X-Crack in Brick Wall.

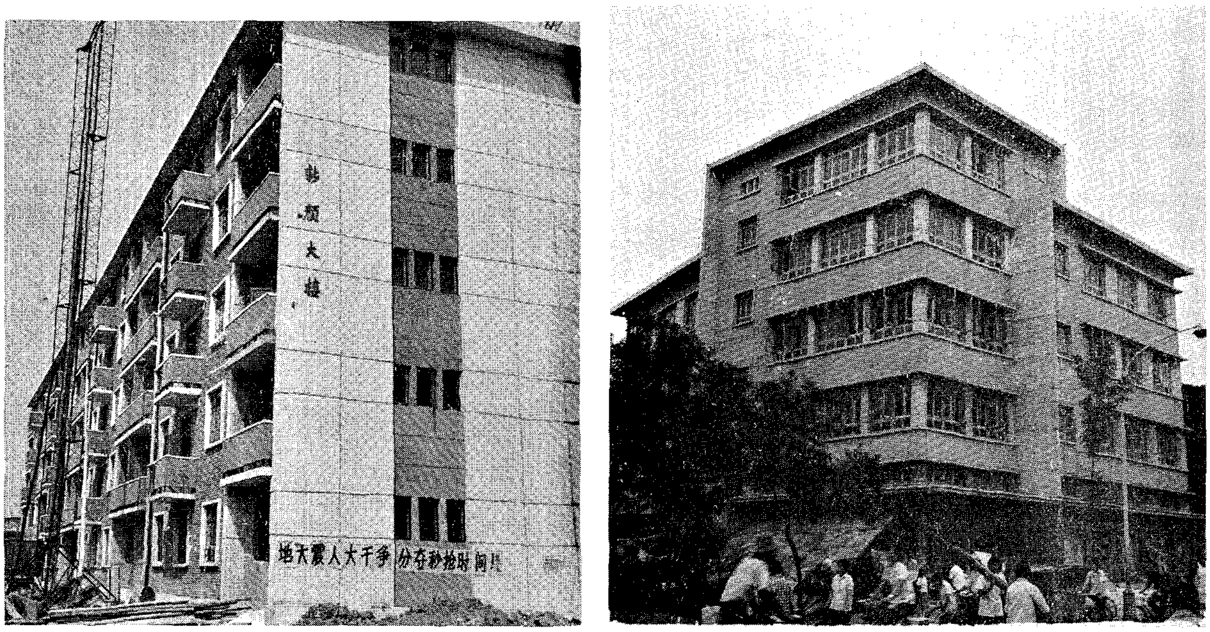


Fig. 22. Undamaged Buildings With Brick Walls and Concrete Floors.

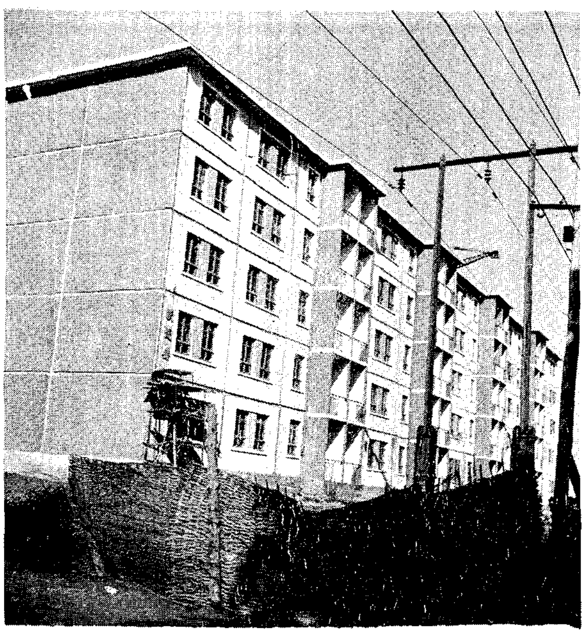


Fig. 23. A Large Panel Structure.

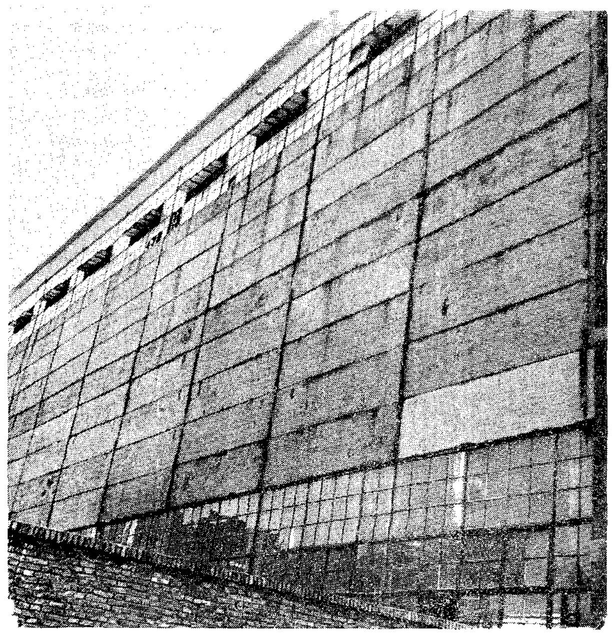


Fig. 24. A Workshop Using Prefabricated Wall Board.

Damage to Concrete-Frame Construction

Some mill buildings with reinforced concrete frames were damaged because of their long fundamental periods. Buildings of this type in Tianjin were damaged because they were located far from the epicenter where the long-period waves diminished slowly; besides, they were on soft soil which also had a long predominant period.

A 13-story frame building (Fig. 25) collapsed on account of its long fundamental period close to the predominant period of the ground and because of its low strength.

A three-story frame textile mill building in urban Tianjin had some columns broken at upper and/or lower ends. After simple repair overcoating the destroyed parts of the columns with reinforced concrete, the building was put back in use. A few months later, during the November 15, 1976 Ninghe earthquake (Magnitude 6.9, epicenter 60 km from Tianjin, intensity in Tianjin VII, maximum acceleration measured by strong motion seismograph 134 gal), this building collapsed.

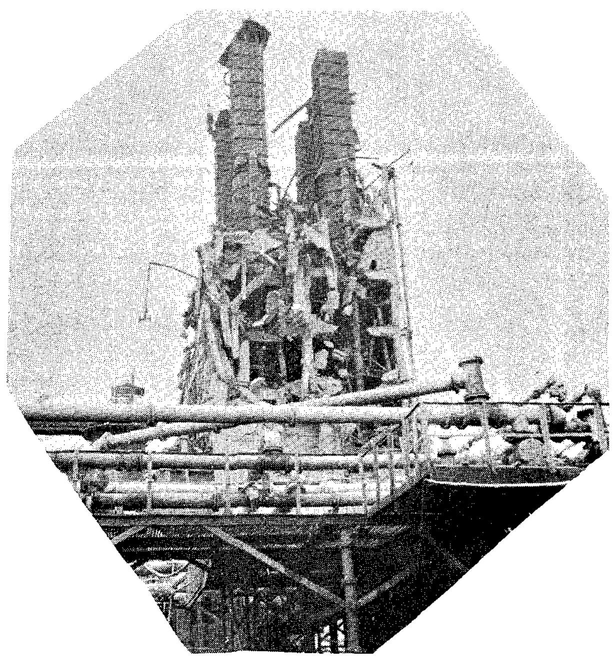


Fig. 25. Collapsed 13-Story Frame Building in Tanggu.

Fig. 26 shows an eight-story reinforced concrete frame hotel with an expansion joint at the center of the building. During the Tangshan earthquake, the walls at both sides of the expansion joint broke due to impact, and many hollow brick infilled walls broke. After the earthquake, this building was restored to its former condition; but during the Ninghe earthquake it broke again, as during the Tangshan earthquake. This means that the frames had deformed to such a large degree that they easily caused destruction of the infilled walls. We conclude that a building should be strengthened rather than merely restored to its original condition as a result of this experience.

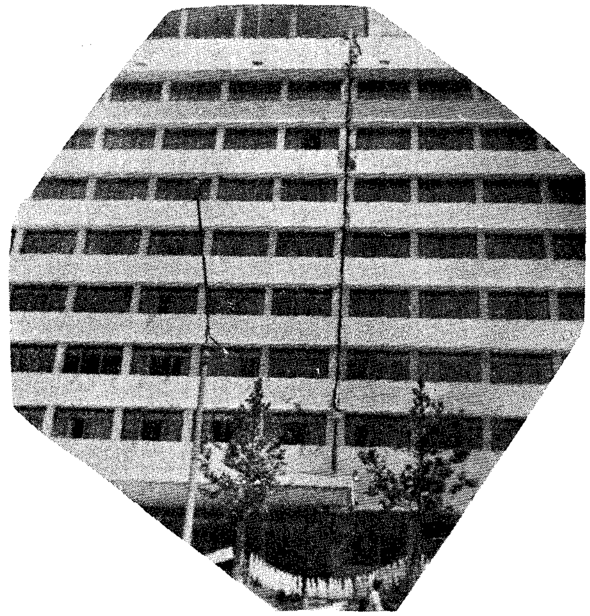


Fig. 26. Tianjin Friendship Hotel Damage.

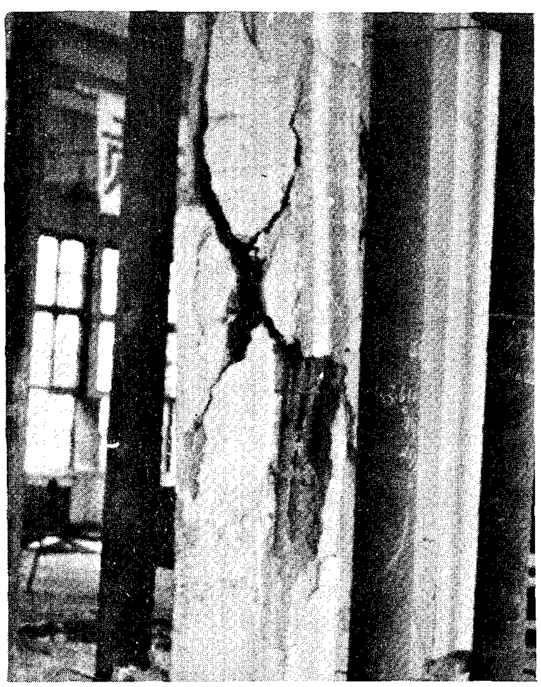


Fig. 27. Shear Failure of Column.

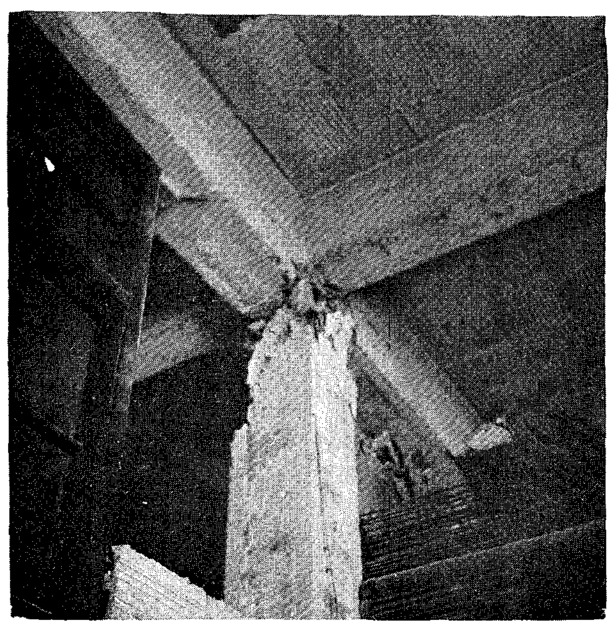


Fig. 28. Bending Failure of End of Column.

Figs. 27 and 28 indicate patterns of broken columns; Fig. 27 shows shear failure, Fig. 28 bending failure.

Fig. 29 shows the damaged tower on the main building of Nankai University. It was damaged during the Tangshan earthquake and fell down during the Ninghe earthquake. Fig. 30 shows the damaged tower of a department store. These are good examples of tip effect.

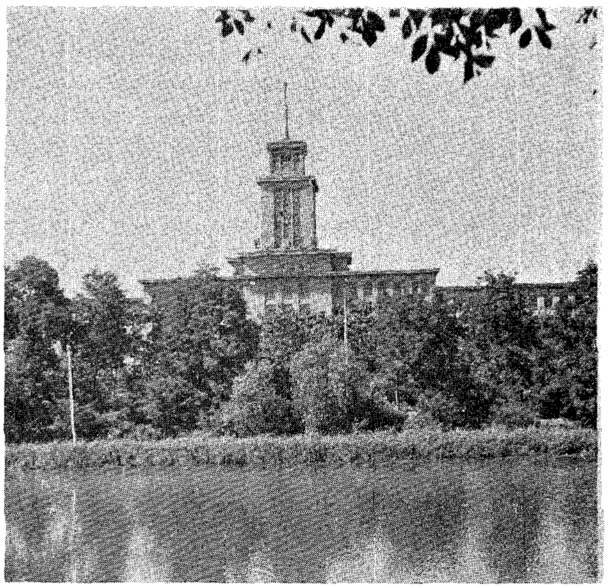


Fig. 29. Damaged Tower in Nankai University.

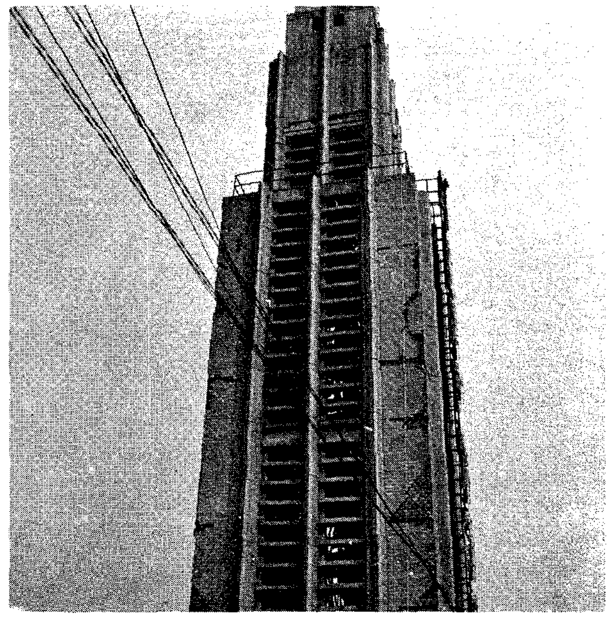


Fig. 30. Damaged Tower in Department Store.

Damage to Single-Story Mill Buildings

In Tanggu (Intensity VIII) many mill buildings with long spans and great height were severely damaged. In Fig. 31 the roof of a very high mill building in Tanggu with reinforced concrete columns, roof trusses, and roof slabs collapsed during the earthquake. The damage was due to the long fundamental period of the mill building and the heavy roof.

Fig. 32 shows a warehouse with reinforced concrete columns, roof trusses, and roof slabs entirely collapsed during the earthquake due to fracture of columns with low carrying capacity.

Fig. 33 is a factory building with reinforced concrete columns, steel roof trusses, and reinforced concrete roof slabs. During the earthquake its eaves and wall collapsed and smashed the neighboring roof. Phenomena like this were numerous.

Fig. 34 is a reinforced concrete frame mill building with a skylight. When the earthquake occurred, the roof was cracked by the damaged skylight and collapsed roof slabs.

Infilled walls of many mill buildings collapsed because the connections between walls and columns were weak. Figs. 35 and 36 are damaged infilled walls of mill buildings. Fig. 37 shows the damage of vertical bracing between columns.

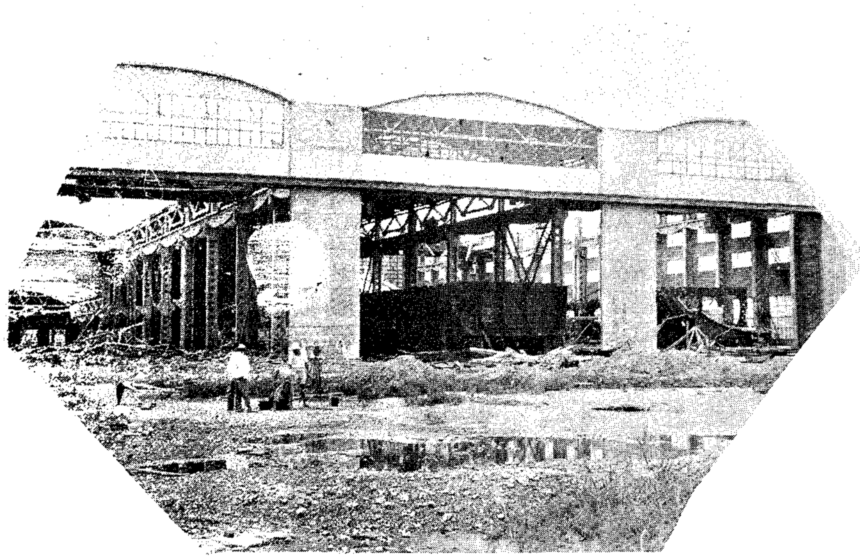


Fig. 31. Collapsed Mill Building in Tangshan.

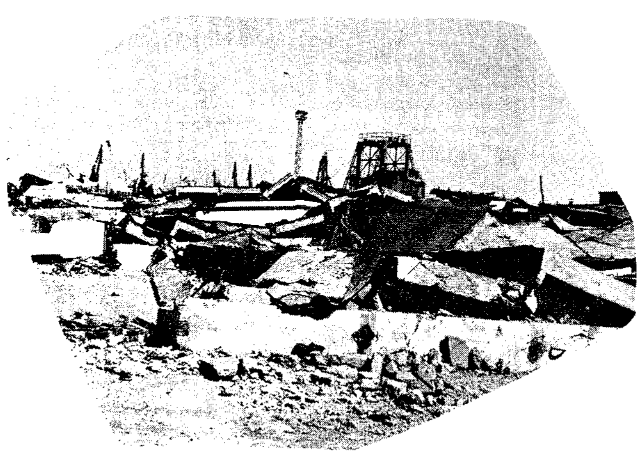


Fig. 32. Collapsed Warehouse in Tanggu.

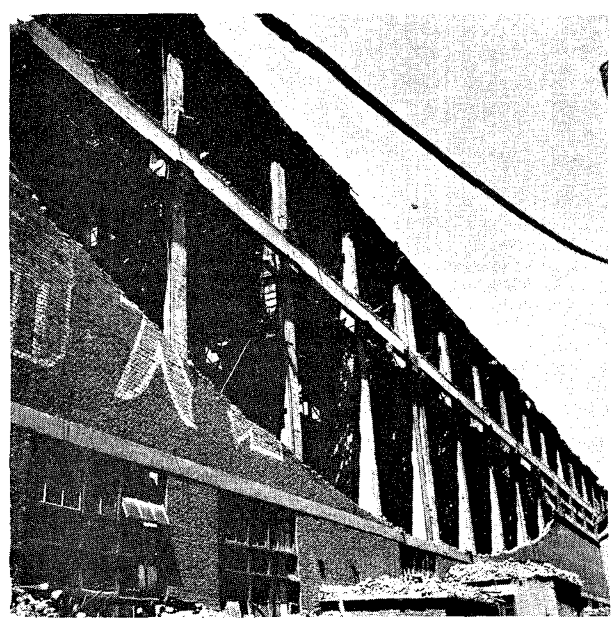


Fig. 33. Damaged Mill Building in Tianjin.

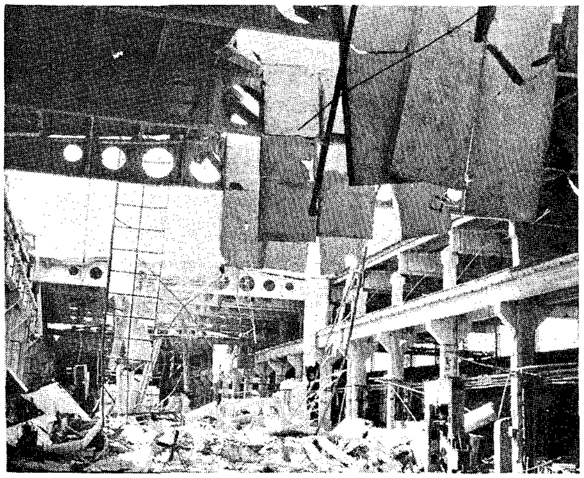


Fig. 34. Cracked Mill Building.

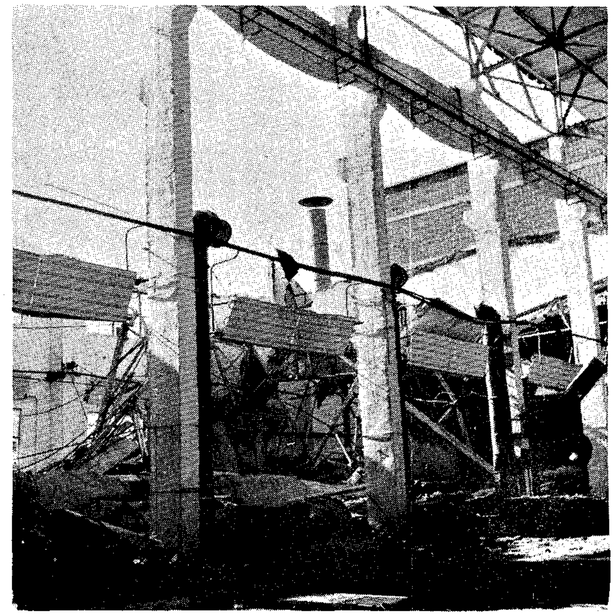


Fig. 35. Damaged Eaves and Walls in a Workshop.

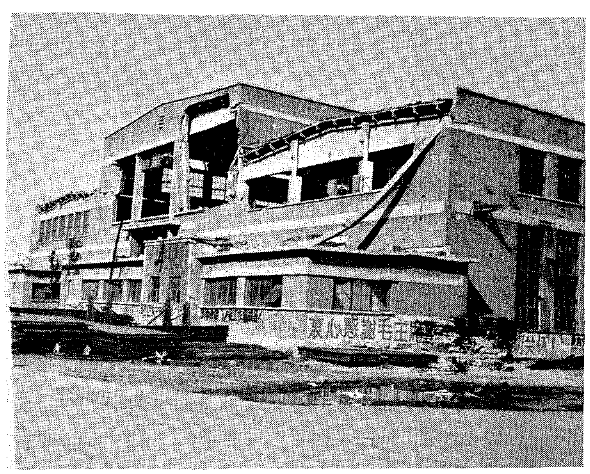


Fig. 36. Damaged End Walls in Factory.

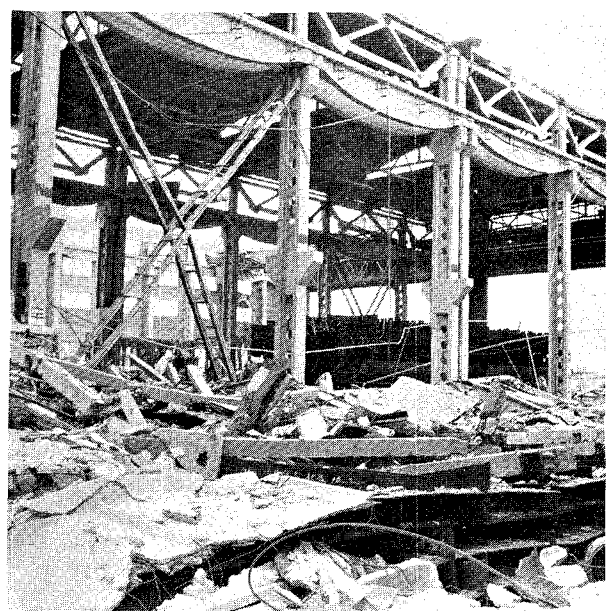


Fig. 37. Damaged Vertical Bracing Between Columns in Building in Tanggu.

Damage to Chimneys and Water Towers

Most of the brick chimneys in urban Tianjin broke. The same phenomenon was observed in Haicheng and Tangshan. Chimneys of this type incurred severe damage in Tianjin near the sea, but far from the epicenter. Damage is also related to their long fundamental period.

Most broke horizontally at upper levels. Upper parts of some chimneys even fell to the ground, as shown in Fig. 38. This is due to the effect of the higher mode of vibration. Even some chimneys, reinforced at the top with steel, did not survive.

Fig. 39 shows a brick chimney that cracked and twisted during the earthquake. The rotation formed gradually by the seismic force acting back and forth as the earthquake occurred.

Many water towers broke or collapsed in areas of Intensity VIII and IX. Fig. 40 shows a water tower in an area of Intensity IX which collapsed due to its low strength.

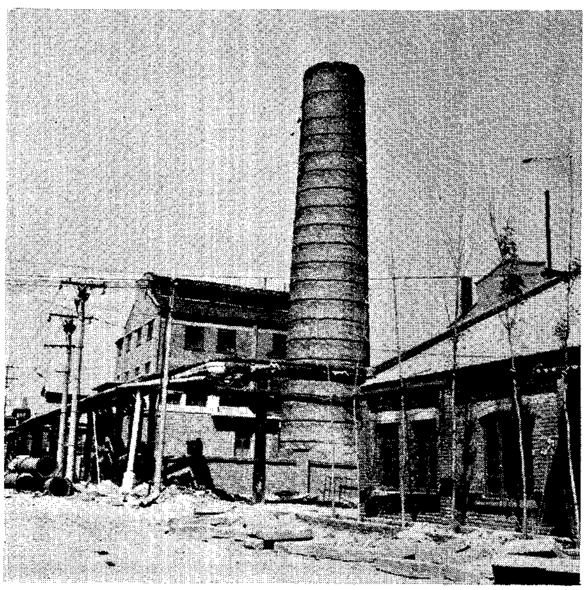


Fig. 38. Horizontally Cracked Brick Chimney; Upper Part Fell Down.

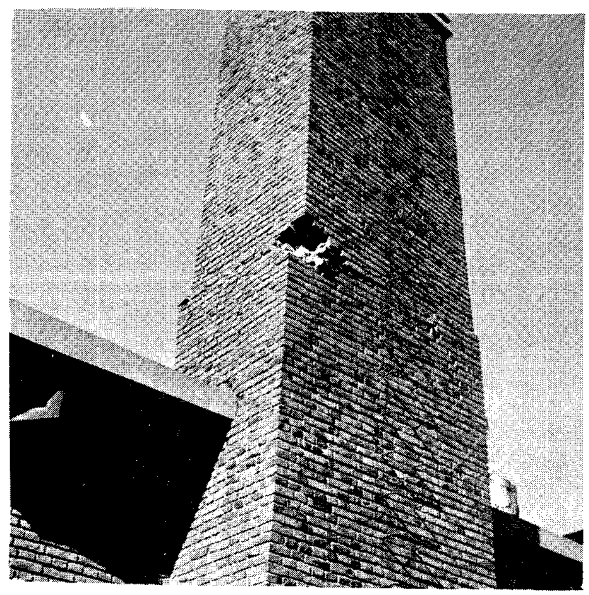


Fig. 39. Twisted Brick Chimney

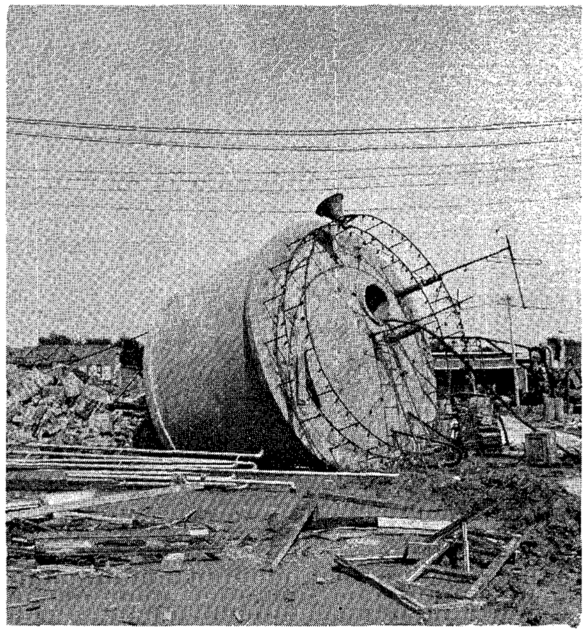


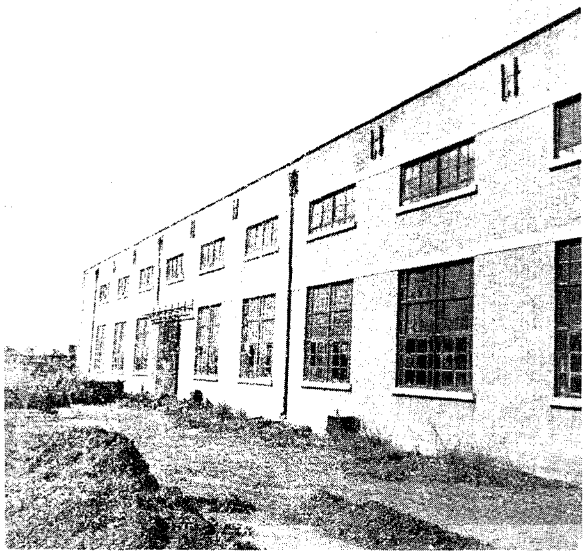
Fig. 40. Collapsed Water Tower in Hangu.

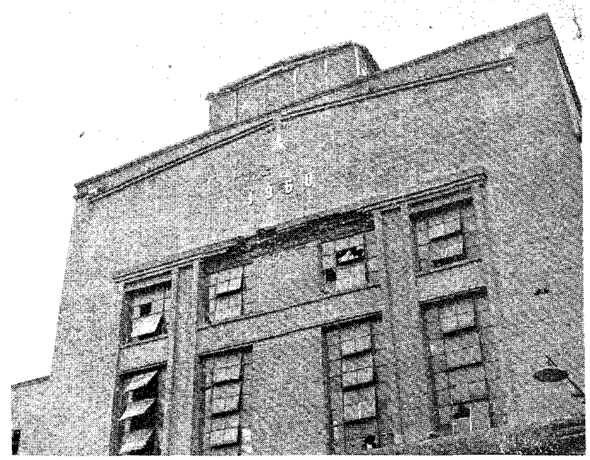
3. Aseismic Strengthening Measures

An important lesson has been learned from the damage suffered in Tianjin during the Tangshan earthquake. That is, the difference of antiseismic capacities is obvious between buildings with aseismic strengthening before the earthquake and those without. Before the earthquake, a midrange earthquake forecast had been given that there would be a strong shock in the northern part of China. After that, some buildings had been strengthened; these suffered less damage during the earthquake than those which had not been so strengthened.

For example, several months before the earthquake all the mill buildings in one factory were strengthened. Connections between infilled walls and columns, as well as roof trusses, were strengthened by bolts; bracing systems of roof trusses were strengthened by steel sections; and reinforced concrete columns were strengthened by steel, as shown in Fig. 41. As a result, during the earthquake no roof in this factory fell down, while only a few infilled walls were broken. Production was restored soon after the earthquake. On the other hand, similar mill buildings nearby collapsed or were severely damaged. This is a very convincing example of the value of aseismic strengthening measures.

Another example also shows that aseismic strengthening is valuable. In Hexi District, Tianjin, about 700 rooms were strengthened before the earthquake. None of these collapsed during the quake (generally they were only lightly dam-





aged. The method of strengthening was to connect exterior and interior walls in single and multiple story brick buildings with steel rods, as shown in Fig. 42. This decreased the probability of collapsed walls during the earthquake, and is a simple but effective method.

To cite another example, brick buildings or brick walls broken after the Tangshan earthquake were repaired and strengthened by use of reinforcing fabrics on interior and exterior walls, followed by application of a layer of mortar 3 to 4 cm thick. On November 15, 1976 when the Ninghe earthquake occurred, most of the strengthened buildings survived.

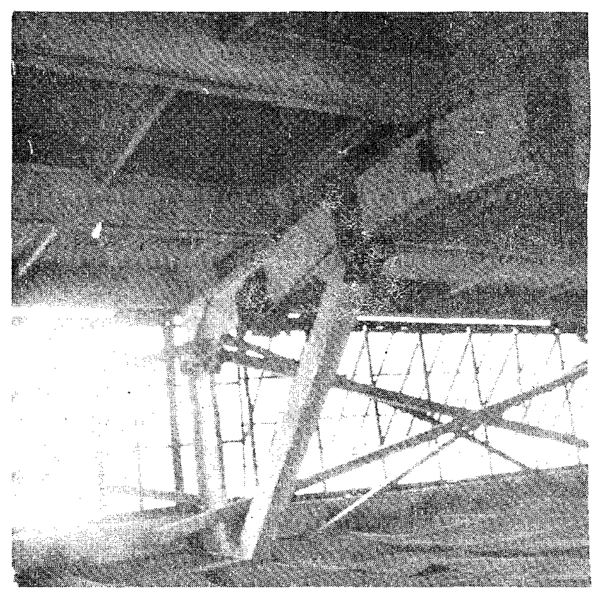


Fig. 41. Strengthened Mill Buildings.

In Tianjin, a large number of buildings have been strengthened and repaired. The main strengthening measures are as follows:

1. Connecting tightly exterior and interior walls of brick buildings with steel rods
2. Strengthening brick walls with reinforced concrete columns which are securely connected to the walls
3. Setting up a girth to each story of brick buildings and connecting girths and walls securely

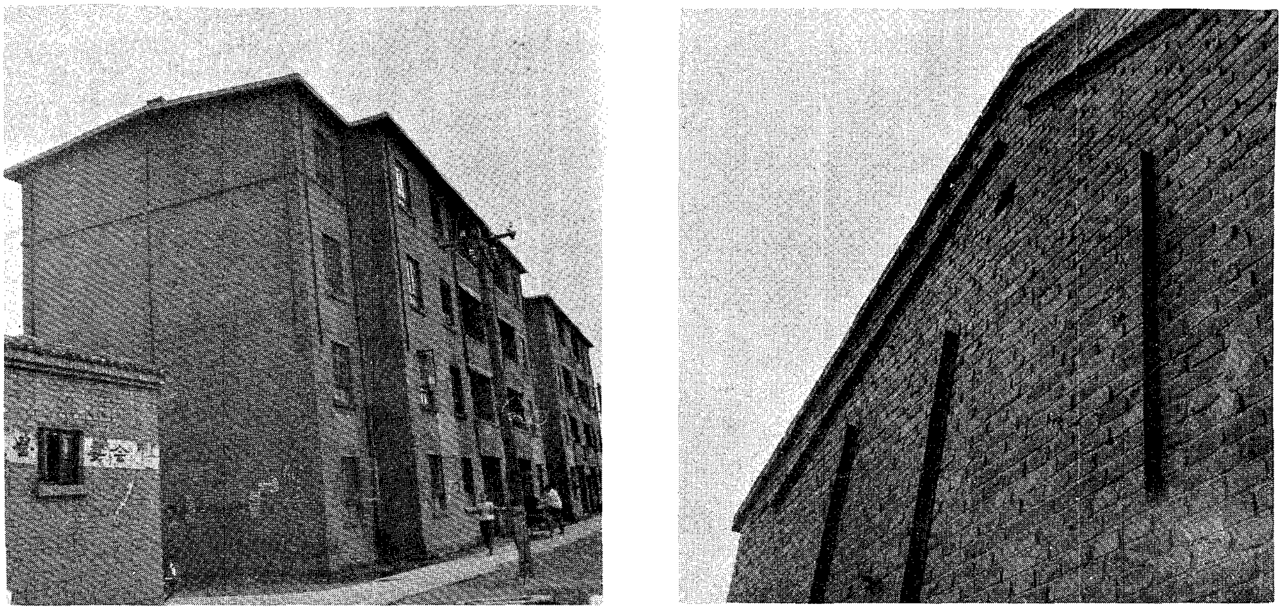


Fig. 42. Strengthened Buildings in Hexi District.

4. Strengthening brick walls with reinforcing fabrics on both sides of walls and adding mortar 3 to 4 cm thick

5. Pressure grouting high-grade mortar into wall crevices

6. Overcoating columns with reinforced concrete

7. Connecting infilled walls and columns, as well as trusses of mill buildings, with bolts

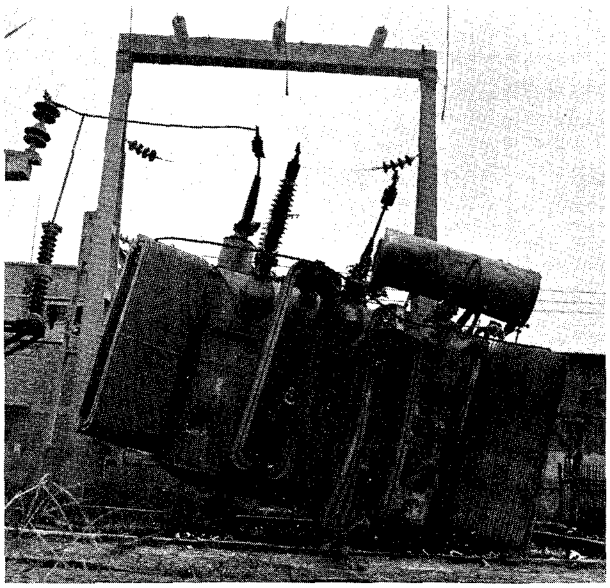
8. Increasing and strengthening braces of mill buildings.

These methods proved effective during the Tangshan earthquake, as shown in Fig. 43.

4. <u>Secondary Damage</u>

During the Tangshan earthquake, some secondary damage exposed the weak points in precautionary measures against earthquakes in the city. Fortunately, the Tangshan earthquake happened at 3:42 a.m., and there were few fire sources, so the number of disastrous fires in Tianjin was small. If the earthquake had occurred during the day, serious fires would have been unavoidable. A part of the pipelines collapsed

A most serious problem was that people were afraid to live in damaged houses; consequently, streets were jammed and nearly all open spaces in residential districts were crowded. Traffic was held up, and buses and cars could not move. Normal order in city life disappeared. Rehabilitation and relief work could hardly be carried out.



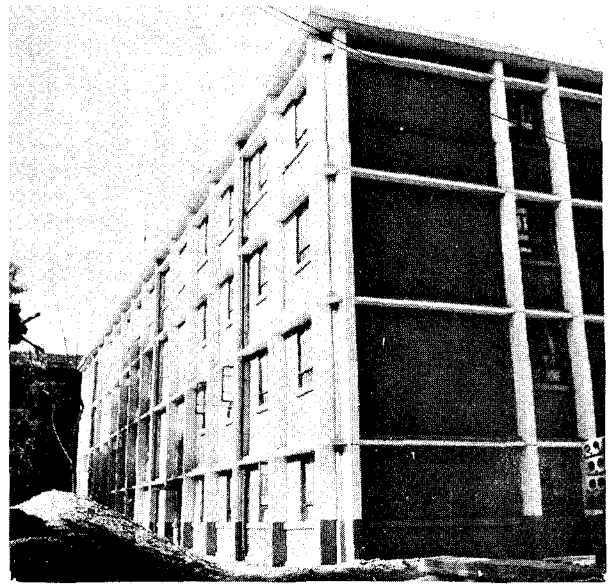


Fig. 43. Strengthened Brick Building With Reinforced Concrete Columns and Girths.

Fig. 44. Burnt Transformer.

Some telephone offices collapsed, and some exchanges were damaged; so telephone service in urban districts and counties was partly broken off. This aggravated the difficulty in rehabilitation work.

Damaged generating equipment and transmission lines hindered production in some factories. For instance, in a steel plant, molten metal solidified in a steel-making furnace. Fig. 44 shows a transformer at a Hangu transformer substation in the area of Intensity IX which burnt out because it fell off its supports.

Gasoline gushed out in an oil depot, but no fire occurred due to prompt cutoff at storage tanks. Pipelines in some factories producing poisonous gas ruptured and gas leaked, but no heavy losses were incurred as a result of effective countermeasures.

Those are the facts we find important in the struggle against natural calamities in a city and deserve attention. However, our summary is preliminary, and comments are solicited.

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EMPIRICAL CRITERIA OF SAND LIQUEFACTION

by

Xie Junfei*

Much attention has been paid to problem of sand liquefaction by Chinese engineers since the well-known Niigata earthquake and the Alaska earthquake of 1964, and the 1966 Xingtai earthquake in China further stimulated research interests among the scientific community. Many works have been done on the post earthquake field investigation and related soil exploration. Some prelimenary results have been obtained after the 1970 Tunghai earthquake. The criteria set up for the threshhold of sand liquefaction in the Chinese aseismic building code (TJ11-74) were based on these results. The 1975 Haicheng earthquake and the 1976 Tangshan earthquake brought us with new information providing opportunities to identify the code provisions and also with some problems for further study.

This paper intends to explain the basis of the provisions in the Chinese code, and introduce some statistical results on liquefaction potential and several remarks on further study.

1. Basis of the Criteria of Liquefaction in Chinese Code

A criteria is specified in the code TJ11-74 as equation (1) to evaluate the liquefaction potential of a given sand layer in situ

$$\overline{N} = \overline{N}'\left[1 + \alpha_s(d_s - 3) + \alpha_w(d_w - 2)\right] \qquad (1)$$

where $\overline{N}'$= critical standard penetration resistance which equal to 6, 10 and 16 for intensity VII, VIII and XI, respectively, when d_s = 3m, d_w = 2m;

d_s= depth of the sand layer under study, in meters;

d_w= ground water level, below the ground surface, in meters;

α_s= 0.125, coefficient of the effect of depth of the sand;

α_w= -0.05, coefficient of the effect of ground water.

No liquefaction will occur in the sand layer when the average penetration resistance obtained in field test is greater than value evaluated by equ. (1) or vice versa.

Equation (1) is formulated in two steps. At first, $\overline{N}'$ is evaluated from the field investigation data accumulated from the recent destructuve earthquakes in China. The data are collected from 12 cases of foundation failure due to sand liquefaction and 58 cases of having macroscopic surface phenomena to be able to distinguish the liquefied and unliquefied sites. Explorations show that the ground water levels in these cases vary from 1 to 3m, with an average of 2m, and the depths of liquefied layers vary from 2 to 4m, with an average of 3m. These data are plotted in Fig. 1, and the critical value ($\overline{N}'$) 6, 10 and 16 can be obtained from the boundary line by direct inspection.

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Next, the simplified procedure proposed by H. B. Seed is used to evaluate the effect of ground water level and depth of the sand. The average seismic shear stress in the sand deposit can be calculated by the following formula [1]

$$\tau_{av} = 0.65 \cdot \frac{\gamma d_s}{g} \cdot a_{max} \cdot r_d \qquad (2)$$

where d_s = depth of the sand layer under study;

γ = unit weight of sand, the natural nuit weight is usually taken as 1.8 T/m^3 and the saturated unit weight as 1.9 T/m^3 ;

$\frac{a_{max}}{g}$ = ratio of max. ground acceleration to that of gravity, which is equal to 0.075, 0.15 and 0.3 respectively for intensity VII, VIII and XI, according to our draft of seismic codes of 1959 and 1964;

r_d = stress reduction coefficient, the values of which are shown in Table 2.

The liquefaction resistance of a sand layer can be evaluated by the following equation

$$[\tau] = C_r \cdot \frac{D_r}{50} \cdot \left[\frac{\sigma_{dp}}{2\sigma_a}\right]_{50} \cdot \sigma_o' \qquad (3)$$

where D_r = relative density of the sand, in %;

$\left[\frac{\sigma_{dp}}{2\sigma_a'}\right]_{50}$ = liquefaction stress ratio for D_r = 50%, determined by dynamic triaxial test, being taken as 0.21 herein;

σ_o' = effective overburden pressure;

C_r = correstion factor to be applied to laboratory triaxial test data to obtain the stress condition causing liquefaction in the field, C_r used later and those proposed by Prof. Seed are plotted in Fig. 2.

The correction factor, C_r , used in the following is determined as follows:

(1) When d_s = 3m, and d_w = 2m, the critical penetration resistance is 6, 10 and 16 for the intensity VII, VIII and XI respectively, the corresponding converted relative density being 50%, 65% and 77%.

(2) By using the data mentioned above, the value of τ_{av}/σ_o' from eq.(2) equals 0.058, 0.116 and 0.231 for intensity VII, VIII and XI respectively.

(3) Based on the experimental relation that the sand liquefaction resistance is proportional to the relative density of sand, $[\sigma_{dp}/2\sigma_a]_{65}$ =0.273 and $[\sigma_{dp}/2\sigma_a]_{77}$ =0.324 may be obtained when $[\sigma_{dp}/2\sigma_a]_{50}$ is taken as 0.21.

(4) From the definition of C_r , i.e. $C_r[\sigma_{dp}/2\sigma_a] = \tau_{av}/\sigma_o'$, the values of C_r are obtained as 0.28, 0.43 and 0.72 corresponding to D_r =50%, 65% and 77%, which are the three points plotted in Fig. 2, and the curve is fitted in with these points.

Now the min. relative density of sand for the unliquefied layer can be determined from the given values of a_{max}/g , d_w and d_s first and, then according to the depth of the layer, convert the min. relative density into the standard penetration resistance. Thus the distribution of the critical penetration value along the layer depth can be evaluated.

In order to obtain the distribution of the min. relative density along the layer depth, let eq. (2) equal to eq.(3), leading to

$$D_r \cdot C_r = \frac{0.65 \times 50}{\left[\frac{\sigma_{dp}}{2\sigma_a}\right]_{50}} r_d \cdot \frac{\gamma d_s}{\sigma_o'} \cdot \frac{a_{max}}{g} \qquad (4)$$

in which the terms on the right hand side are known values. And from the $C_r \sim D_r$ Curve in Fig. 2, D_r and the corresponding value N can thus be obtained.

The critical standard penetration resistance is computed for the following:

(1) The depth of ground water level varies from 1 to 5 m;

(2) The depth of sand under study, from 1 to 10 m;

(3) The intensity rating, from VII to XI.

When $d_s = 3$m, $d_w = 2$m, the computed N values are 5, 9 and 16 corresponding to the intensity VII, VIII and XI respectively. There is no much difference between the computed values and those evaluted from Fig. 1 (The corresponding values computed by using Seed's C_r are 2, 5 and 14 respectively).

This fact showed that the adopted values of parameters were appropriate, but, in contrast with direct use these computed critical N values, we used only the ratio, α , of critical values for various conditions to that for $d_s = 3$m, and $d_w = 2$m (Table 3). The ratio is a function of a_{max}/g , d_s and d_w . The effects of $[\sigma_{dp}/2\sigma_a]_{D_r}$ and a_{max}/g on α are very small.

Neglecting the effect of a_{max}/g on α , and expressing the effect of d_s and d_w in a form $\alpha = 1 + \alpha_s(d_s - 3) + \alpha_w(d_w - 2)$, the influence coefficients $\alpha_s = 0.125$ and $\alpha_w = -0.05$ are obtained from the α values in Table 3.

From the derivation process of eq.(1), it must be noted that eq.(1) holds only when d_s is less than 15m and only for horizontal ground.

Considerable cases of sand liquefaction occurred in the 1975 Haicheng earthquake and the 1976 Tangshan earthquake. Special field investigation were made to check the reliability of eq.(1). One of the results is plotted in Fig. 3. It shows that, in the area of intensity VII and VIII, the discrimination is basically in agreement with the actual phenomena.

2. Statistical Analysis of Liquefaction Potential

It is apparent that the criteria, such as the straight line drawn by inspection in Fig. 1, used to discriminate whether sand liquefaction may occur or not is a subjective one and its reliability is ambiguous. Moreover, it is not convenient to include more influence factors in this approach. In order to overcome the limitation, a statistical analysis of liquefaction potential has been suggested.

Suppose the liquefaction potential, Z ,is a linear function of the influence factors, X_i :

$$Z = L_1X_1 + L_2X_2 + \cdots\cdots + L_KX_K \tag{5}$$

where $X_i \ (i = 1, 2, \cdots k)$ = influence factors, e.g. magnitude, relative density, etc.

$L_i \ (i = 1, 2, \cdots k)$ = coefficients to be determined.

Coefficients L_i are determined by Fisher's principle which requires that the difference between the average values $\bar{Z}$ of the liquefaction group and the no-liquefaction group should be as large as possible, but the variance of Z in each group should be as small as possible. The Fisher's principle will be satisfied, if the target function

$$G = \frac{(\bar{Z}^{(1)} - \bar{Z}^{(2)})^2}{\sum_{p=1}^{2} \sum_{j=1}^{n_p} (Z_j^{(p)} - \bar{Z}^{(p)})^2} \tag{6}$$

reaches a max. In eq.(6), $Z^{(1)}$ and $Z^{(2)}$ are the liquefaction potentials for the group of liquefaction and of no liquefaction respectively. $\bar{Z}^{(1)}$ and $\bar{Z}^{(2)}$ are the average of these two groups and $Z_j^{(p)}$ is the Z value of the j^{th} event in the p^{th} group (p =1, 2). n_p is the number of events belonging to group p .

G is a function of L_i . In order to make G a max., partially differentiate G with respect to L_i and let it equal to zero, and thus a set of linear equations containing L_i as unknown is obtained. And L_i is determined by solving the set of equations.

K. Tanimoto had used this statistical approach to analyse the liquefaction of sand [2] . Similar approach has been used by us with two modifications. Firstly, more data are used in the analysis, including both the foreign and Chinese data. Secondly, the accuracy of discrimination is raised by using equation of quadratic form to express liquefaction potential.

When 4 influence factors are taken into consideration, the liquefaction potential has the form

$$\begin{aligned} Z = {} & L_1X_1 + L_2X_2 + L_3X_3 + L_4X_4 \\ & + L_5X_1^2 + L_6X_1X_2 + L_7X_1X_3 + L_8X_1X_4 \\ & + L_9X_2^2 + L_{10}X_2X_3 + L_{11}X_2X_4 \\ & + L_{12}X_3^2 + L_{13}X_3X_4 \\ & + L_{14}X_4^2 \end{aligned} \tag{7}$$

where X_1 = ground water level, m;
X_2 = max. ground acceleration, g;
X_3 = standard penetration resistance;
X_4 = depth of sand under study, m.

When 6 influence factors are taken into consideration, the equation is

$$\begin{aligned} Z = {} & L_1X_1 + L_2X_2 + L_3X_3 + L_4X_4 + L_5X_5 + L_6X_6 \\ & + L_7X_1^2 + L_8X_1X_2 + L_9X_1X_3 + L_{10}X_1X_4 + L_{11}X_1X_5 + L_{12}X_1X_6 \\ & + L_{13}X_2^2 + L_{14}X_2X_3 + L_{15}X_2X_4 + L_{16}X_2X_5 + L_{17}X_2X_6 \\ & + L_{18}X_3^2 + L_{19}X_3X_4 + L_{20}X_3X_5 + L_{21}X_3X_6 \\ & + L_{22}X_4^2 + L_{23}X_4X_5 + L_{24}X_4X_6 \\ & + L_{25}X_5^2 + L_{26}X_5X_6 \\ & + L_{27}X_6^2 \end{aligned} \tag{8}$$

where X_1 = magnitude;
X_2 = epicentral distance, km;
X_3 = standard penetration resistance;
X_4 = depth of sand under study, m;
X_5 = ground water level, m;
X_6 = duration of ground motion, sec.

Coefficients L_i determined from the data in Table 4 (including 45 events with 6 influence factors and 63 events with 4 factors) are listed in Table 5.

Liquefaction potential in each event listed in Table 4 can be calculated by eq.(7) or eq.(8). Assuming that the distribution $f(Z)$ of liquefaction potential for both groups are normal distribution (Fig.4), a critical value Z_0 is defined as follows.

When $Z < Z_0$, no liquefaction will occur or vice versa. Then the ratio of the successful discrimination is given by

$$P_1 = \frac{\int_{Z_0}^{\infty} f_1(Z)\,dz}{\int_{-\infty}^{\infty} f_1(Z)\,dz} \tag{9}$$

for the group of liquefaction, and

$$P_2 = \frac{\int_{-\infty}^{Z_0} f_2(Z)\,dZ}{\int_{-\infty}^{\infty} f_2(Z)\,dz} \tag{10}$$

for the group of no liquefaction.

If the value of Z_0 is taken so as to give an equal ratio of successful discrimination to each group, i.e.

$$P = P_1 = P_2 \tag{11}$$

Z_0 can then be determined. Substituting Z_0 in eq.(9), P may be obtained as follows
for eq.(8) considering 6 influence factors, $Z_0 = 4.199$, $P = 99\%$,
for eq.(7) considering 4 influence factors, $Z_0 = -2.614$, $P = 92\%$.

Some of the results computed by eq.(8), eq.(5) and eq.(1) for events listed in Table 4 are presented in Table 6 and plotted in Fig.5. Eq.(8) with 6 factors gives correct discrimination for all events; eq.(5) with 6 factors gives wrong results for 5 events listed in Table 6; eq.(1) also had a wrong decision among the 5 events.

3. Some Problems to Be Further Investigated

1) Discrimination of liquefaction in-situ.

Discrimination of liquefaction in a site (or the depth of liquefaction) according to the macroseismic phenomena is an important, but not yet solved problem. Whether liquefaction occurs or not is often discriminated by the occurrence of sandblows, especially when there are no buildings on the ground. An example showed that although there was no evidence of ground cracks and sandblows, the saturated fine sand ($\bar{N}=3$), 4-6m under the ground surface, did liquefy during earthquake. But the surface clay layer prevented the spouting of sand and water. Therefore, when there is a hard clayey soil layer on the ground surface, judgements must be made from field investigation and exploration. It is better to observe the developing and dissipating process of pore pressure during earthquake by measurement so that evaluation of liquefaction in-situ can be directly made.

2) Evaluation of the effect of liquefaction.

Large settlement or tilting of upper structure may often be induced by sand liquefaction, and sometimes overturn of buildings may occur. But sand liquefaction need not in all cases induce damage to the upper structures. In the 1975 Haicheng earthquake, there were many small dwellings and chimneys situated in the liquefied areas. There were many sandblows around these structures, even some occurred indoors.

But no settlement or tilting of these structures were found. The reason is probably that there was a 2-4m thick clay layer (especially the top of it was frozen) over the liquefied sand layer, so that it had sufficient strength to support the shallow, light weighted foundation of the dwelling and that failure of foundation was thus avoided. But theoretical investigation must be made for the quantitative evaluation of the effect of liquefaction.

3) Area of "safe island" against liquefaction.

Increase of effective overburden pressure by filled land is an effective method to raise the liquefaction resistance of the underlying sand layer. The Niigata earthquake in Japan and the Xingtai earthquake in China both provided successful examples. At present, the depth of the fill required can be evaluated preliminarily, but the area of the fill is difficult to estimate. From the experience of the Xingtai earthquakem fill land of 0.5 sq. km is sufficient as an "safe island" again liquefaction. But the experience of the Haicheng earthquake showed that only 0.3 sq. km of fill is required. However, area of the "safe island" correlates with many factors, such as the density of sand, seismic stress, duration of ground motion and drainage condition, etc. It should be investigated by detailed analysis.

4) Application of laboratory test results to the discrimination of liquefaction.

Triaxial compression test, simple shear test and torsion-shear test are currently used to simulate the seismic stress condition for the study of the influence factors of liquefaction and its mechanism. No doubt, this is a neccessary and effective approach. However, since the laboratory test condition differ much from the field conditions, it is very hard to determind the field liquefaction resistance by triaxial test. The usual effort to overcome this limitation is continually imporving the instruments and test method to approach the field conditions. However, because there are a lot of difficulties to be met, so at last, it is inevitable to adopt a correction factor determinted by judgement. The writer prefers to use simple instruments and test precedure for measuring the stress ratio causing liquefaction. Although a ratio so determined may differs much from the actual one, in my opinion, it is still an important parameter expressing the relative liquefaction resistance. It would be a useful procedure to use this stress ratio as a liquefaction influence factor in statistical analysis.

<u>References</u>

1. H. B. Seed, I. M. Idriss, "Simplified Procedure for Evaluating Soil Liquefaction Potential", Journal of the Soil Mechanics and Foundation Division, ASCE, vol.97, no.SM9, 1971.
2. K. Tanimoto and Tsutomu Noda (1976), "Prediction of Liquefaction Occurrence of Sandy Deposits During Earthquak By A Statistical Method", Proceedings of the Japan Society of Civil Engineers, no.256, 1976-12.

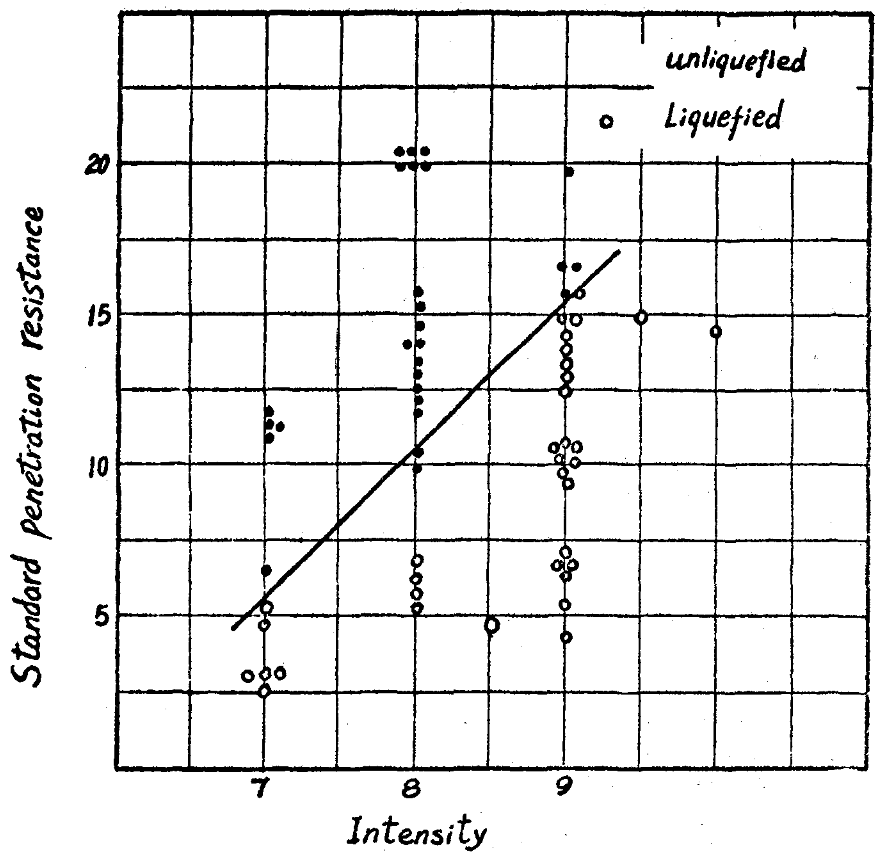


Fig. 1 Filed Exploration Data from Six Earthquakes and Boundary Line Between Liquefied and Unliquefied Cases.

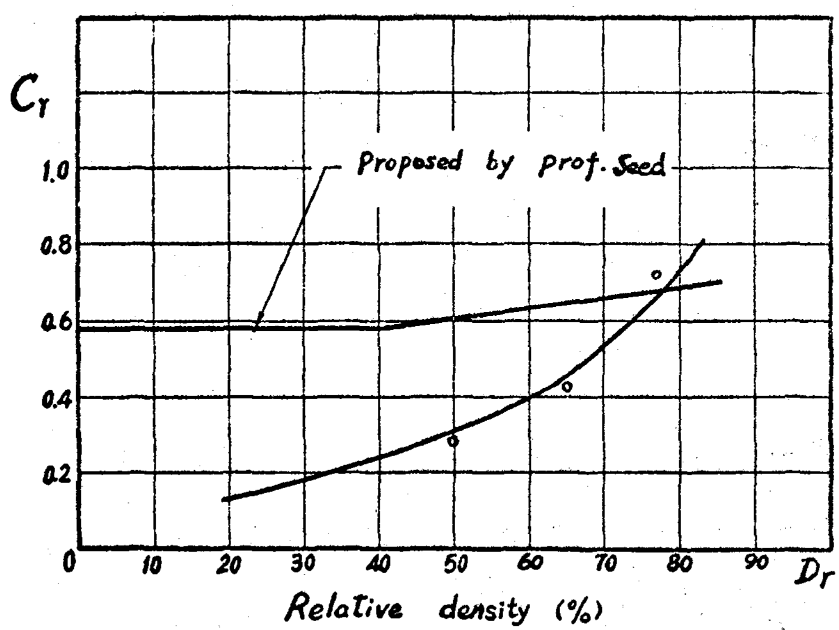


Fig. 2. Correction Factor C_r

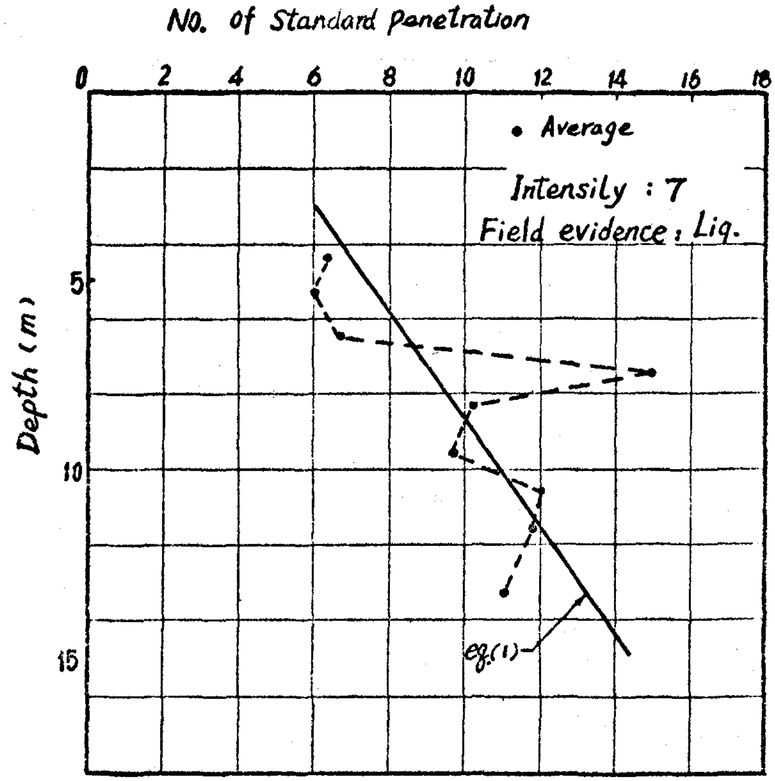


Fig.3. An Examples for Checking the Provisions in Chinese Aseismic Code

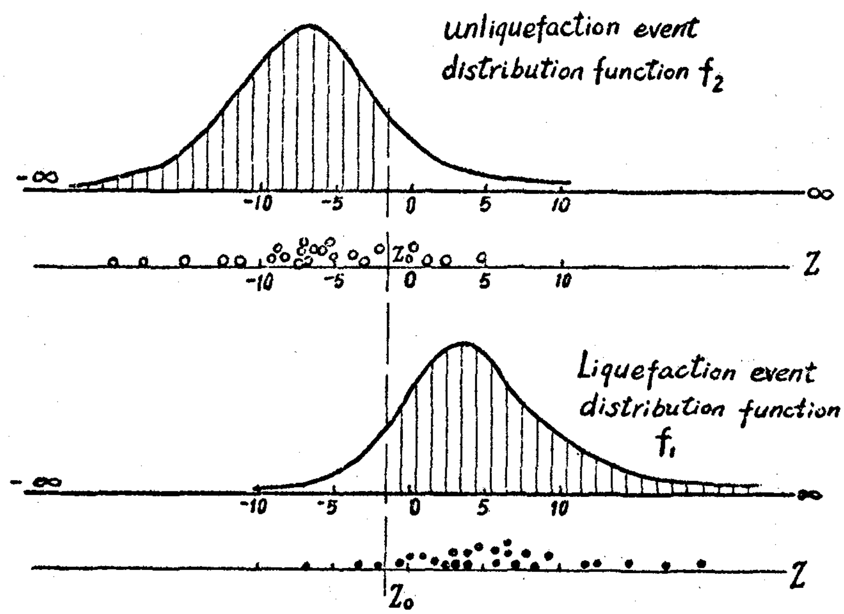
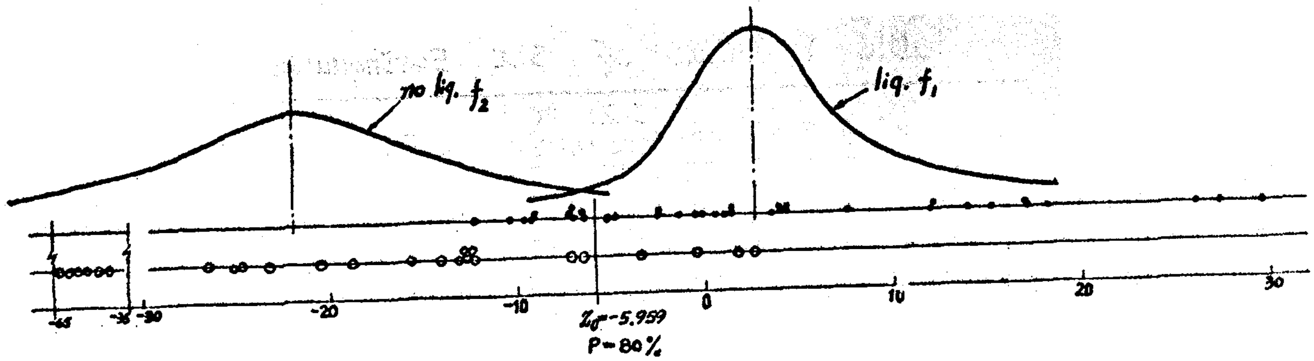
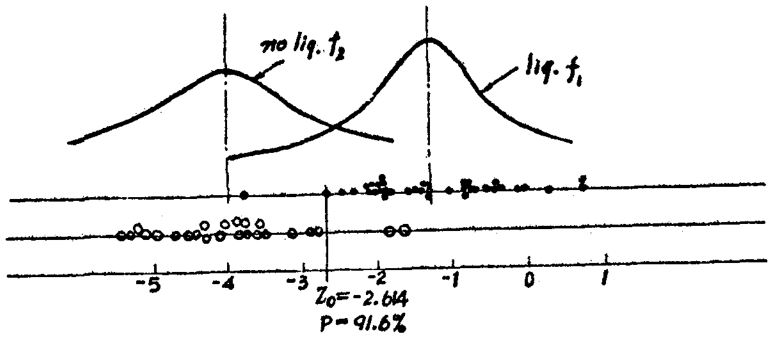


Fig.4 The Definition of Critical Liquefaction potential

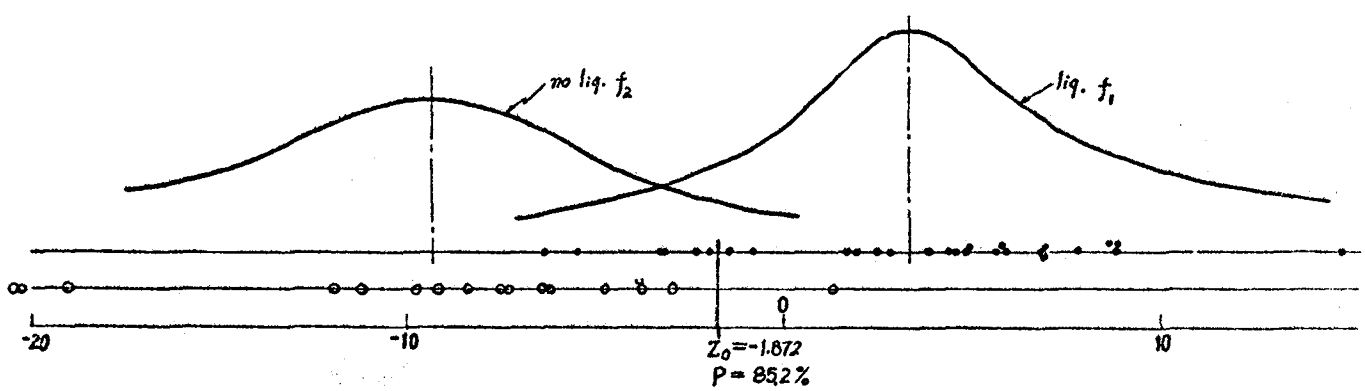


Based on Eq. 5 (linear form)

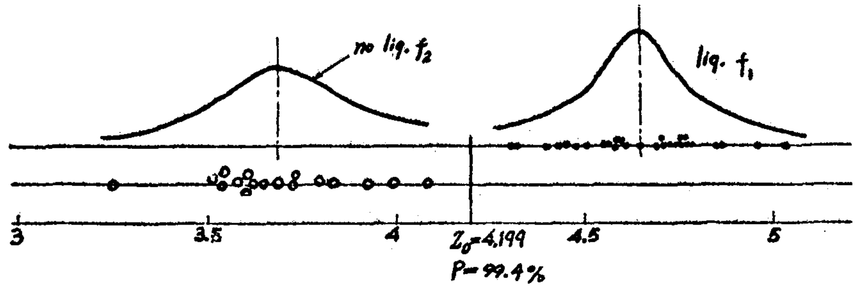


Based on Eq. 8 (Quadratic form)

(a) Considering Four Influence Factors (Using 63 events)



Based on Eq. 5 (linear form)



Based on Eq. 8 (Quadratic form)

(b) Considering Six Influence Factors (Using 45 events)

Fig. 5 THE STATISTICAL ANALYSIS RESULTS

Table 1 Data of Six Earthquakes

Name of Earthquakes	Data of occurrence	Magnitude	Epicentral Intensity
Heyuan Eqk. Guang Dong prov.	1962·3·19	6.4	VIII
Xingtai Eqk. Hebei prov.	1966·3·8	6.8	XI
Xingtai Eqk. Hebei prov.	1966·3·22	7.2	X
Bohai Eqk. Shandong Prov.	1969·7·18	7.4	VII
Yangjiang Eqk. Guang Dong prov.	1969·7·26	6.4	VIII
Tonghai Eqk. Yunnan prov.	1970·1·5	7.8	X

Table 2. Average of r_d

d_s(m)	0	1	2	3	4	5	6	7	8	9	10
r_d	1.00	0.99	0.98	0.97	0.96	0.955	0.95	0.94	0.93	0.92	0.91

Table 3. Values of α

d_w(m)	1			2			3			4			5		
d_s (m) \ I	7°	8°	9°	7°	8°	9°	7°	8°	9°	7°	8°	9°	7°	8°	9°
1	0.56	0.64	0.66												
2	0.86	0.90	0.94	0.85	0.79	0.89									
3	1.12	1.10	1.10	1.00	1.00	1.00	0.78	0.89	0.90						
4	1.22	1.26	1.24	1.20	1.23	1.10	1.04	1.12	1.00	0.92	1.04	1.04			
5	1.40	1.40	1.37	1.32	1.31	1.29	1.16	1.19	1.18	1.10	1.08	1.19	1.06	1.15	1.15
6	1.56	1.54	1.54	1.44	1.44	1.37	1.28	1.28	1.32	1.24	1.24	1.26	1.28	1.28	1.26
7	1.68	1.64	1.65	1.56	1.55	1.50	1.44	1.53	1.42	1.42	1.44	1.41	1.44	1.36	1.40
8	1.78	1.74	1.66	1.69	1.63	1.60	1.62	1.65	1.57	1.52	1.58	1.55	1.56	1.62	1.57
9	1.88	1.82	1.75	1.80	[illegible]	[illegible]	1.75	1.81	1.72	1.68	1.73	[illegible]	[illegible]	[illegible]	[illegible]
10	2.00	1.94	1.84	1.90	[illegible]	[illegible]	1.90	[illegible]	1.80	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 4

Case number	Earthquake	Date	Site	Magnitude	Epicentral Distance (Km)	Soil type	Depth of water table (m)	Depth Under Study (m)	Penetration value at depth under Study	Max. Ground Surface acceleration (g)	Duration of Shaking (sec)	Liquefaction	
1	Niigata	1802	Niigata	6.6	39	Sand	1	6	6	0.12	20	No	
2	Niigata	1802	Niigata	6.6	39	Sand	1	6	12	0.12	20	No	
3	Niigata	1887	Niigata	6.1	47	Sand	1	6	6	0.08	12	No	
4	Niigata	1887	Niigata	6.1	47	Sand	1	6	12	0.08	12	No	
5	Mino-Owari	1891	Unuma	8.4	32	Sand & gravel	2	7.5	19	0.35	75	No	
6	Fukui	1948	Takaya	7.2	6	Sand	1	7	28	0.30	30	No	
7	Chile	1960	Puerto Montt	8.4	113	Sand	3.5	6	18	0.15	75	No	
8	Chile	1960	Conception	8.4	113	Fluvial	3.5	7	10	0.15	20	No	
9	Chile	1960	Huachipato	8.4	113	Beach	3.5	8	35	0.15	20	No	
10	Niigata	1964	Niigata (with fill)	7.5	52	Fluvial	3.5	8.5	7	0.16	20	No	
11	Niigata	1964	Niigata (Zone B)	7.5	52	Older-Fluvial	1	6	12	0.16	20	No	
12	Niigata	1964	Niigata	7.5	52	Sand	1	6	12	0.16	40	No	
13	Niigata	1964	Niigata	7.5	52	Sand	3.5	7.5	6	0.16	40	No	
14	Alaska	1964	Quartz Creek	8.3	113	Sandy gravel	0	7.5	35	0.12	180	No	
15	Tokachi-Oki	1968	Hachinohe	7.8	172	Sand	1	3.5	14	0.21	45	No	
16	Tokachi-Oki	1968	Hachinohe	7.8	172	Sand	1.5	3	15	0.21	45	No	
17	Tokachi-Oki	1968	Hachinoho	7.8	172	Beach	1.5	3.5	18	0.21	20	No	
18	Kern County	1952	Kern Station	—	—	—	3.5	6.0	(9)	0.25	—	No	
19	Chile	1960	Huachipano	—	—	—	3	9	(35)	0.25	—	No	
20	Chile	1960	Huachipano	—	—	—	3	22.5	(35)	0.25	—	No	
21	Haicheng	1974	Shuangtaihe gate	7.3	90	Silt	1	8	15	0.075	—	No	
22	Haicheng	1974	Shuangtaihe gate	7.3	90	Silt	1	12	20	0.075	—	No	
23	Haicheng	1974	Shuangtaihe Eardo Bridge	7.3	90	Fine sand	2	6	9.5	0.075	—	No	
24	Haicheng	1974	Shuangtaihe Eardo Bridge	7.3	90	Fine-sand	2	12	15.5	0.075	—	No	
25	Haicheng	1974	Shenglitang	7.3	104	Sand	2	13	14.5	0.075	—	No	
26	Mino-Owari	1891	Ogaki	8.4	32	Sand	1	5	4	0.35	75	yes	
27	Mino-Owari	1891	Ginan West	8.4	32	Sand	2	9	10	0.35	75	yes	
28	Mino-Owari	1891	Ogase pond	8.4	32	Sand	2.5	4	10	0.35	75	yes	
29	Santa Barbara	1925	Shefield Dam	6.3	11	Sand	4.5	7.5	(3)	0.20	15	yes	
30	El Centro	1940	Brawley	7.0	8	Sand	4.5	4.5	9	0.25	30	yes	
31	El Centro	1940	All-Am. Canal	7.0	8	Sand	6	7.5	4	0.25	30	yes	
32	El Centro	1940	Solfatara Canal	7.0	8	Sand	1.5	6	1	0.25	30	yes	

Table 4 (Continue)

Case number	Earthquake	Date	Site	Magnitude	Epicentral Distance (Km)	Soil type	Depth of watertable (m)	Depth under study (m)	Penetration Value at depth under Study	Max. Ground Surface Acceleration (g)	Duration of Shaking (sec)	Liquefaction
33	Tonankai	1944	Komei	8.3	161	Sand	1.5	4	4	0.08	70	Yes
34	Tonankai	1944	Meiko St.	8.3	161	Sand & silt	0.6	2.5	1	0.08	70	Yes
35	Fukui	1948	Takaya	7.2	6	Sand	3.5	4	12	0.30	30	Yes
36	Fukui	1948	Shonenji Temple	7.2	6	Sand	1	3	3	0.30	30	Yes
37	Fukui	1948	Agr. Union	7.2	6	Sand & silt	1	6	5	0.30	30	Yes
38	San Francisco	1957	Lake Merced	5.5	6	Sand	2.5	3.0	7	0.18	18	Yes
39	Chile	1960	Puerto Montt	8.4	113	Sand	3.5	4.5	6	0.15	75	Yes
40	Chile	1960	Puerto Montt	8.4	113	Sand	3.5	4.5	8	0.15	75	Yes
41	Niigata	1964	Niigata	7.5	52	Sand	1	6	6	0.16	40	Yes
42	Niigata	1964	Niigata	7.5	52	Sand	1	7.5	8	0.16	40	Yes
43	Niigata	1964	Niigata (zone c)	7.5	52	Fluvial	1	6	7	0.16	20	Yes
44	Alaska	1964	Snow River	8.3	97	Sand	0	6	5	0.15	180	Yes
45	Alaska	1964	Snow River	8.3	97	Sand	2.5	6	5	0.15	180	Yes
46	Alaska	1964	Scott Glacier	8.3	89	Sand	0	6	10	0.18	180	Yes
47	Alaska	1964	Valdez	8.3	56	Sand	1.5	6	13	0.25	180	Yes
48	Caracas	1967	Karabared	6.3	56	Sand	1	1	3	0.13	15	Yes
49	Tokachi-oki	1968	Hachinohe	7.8	172	Sand	1	3.5	6	0.21	45	Yes
50	Tokachi-oki	1968	Hachinohe	7.8	172	Fill	1.5	3.5	6	0.21	20	Yes
51	Tokachi-oki	1968	Hakodate	7.8	283	Sand	1	4.5	6	0.18	45	Yes
52	San Fernando	1971	SFO. Juvenile Hall	6.6	8	Sandy silt	4.7	6.1	2	0.40	15	Yes
53	San Fernando	1971	Jensen Plant	6.6	8	Silty Sand	16.8	16.8	24	0.35	15	Yes
54	San Francisco	1971	Jensen Plant	—	—	—	16.5	16.5	(6)	0.35	—	Yes
55	Haicheng	1974	Ligohe Chemical fertilizer plant	7.3	95	silt & Fine Sand	1.5	5.2	5.5	0.075	—	Yes
56	Haicheng	1974	Ligohe chemical fertilizer plant	7.3	95	Sand	1.5	6.2	6	0.075	—	Yes
57	Haicheng	1974	Panjin Cold-Storage	7.3	57	muddy silt	1.5	7	6	0.075	—	Yes
58	Haicheng	1974	Yingkou paper plant	7.3	53	Silt	1	10.5	11	0.15	—	Yes
59	Haicheng	1974	Nanheyan Irrigation Station	7.3	60	Sand	2	3	6	0.075	—	Yes
60	Haicheng	1974	Shuiyuan Commune	7.3	—	Sand	2	10	9	0.15	—	Yes
61	Haicheng	1974	Yingkou gate	7.3	55	Sand	2	10.3	9	0.15	—	Yes
62	Tangshan	1976	Weigezhuang	7.8	43	Fine Sand	1.35	2.3	11	0.15	—	Yes
63	Tangshan	1976	Lujiatuo mine	7.8	25	Fine Sand	1	7	4	0.30	—	Yes

Table 5 Coefficient L_i

Coefficient L_i	Variable	Value for Six factors	Variable	Value for four factors
L_1	x_1	1.00000	x_1	1.0000
L_2	x_2	−0.03949	x_2	−2.4153
L_3	x_3	−0.24427	x_3	−0.43627
L_4	x_4	0.02415	x_4	−0.0904
L_5	x_5	1.3593	x_1^2	0.31155
L_6	x_6	0.05416	x_1x_2	−1.6301
L_7	x_1^2	−0.03392	x_1x_3	0.04316
L_8	x_1x_2	0.00482	x_1x_4	−0.43766
L_9	x_1x_3	0.01725	x_2^2	−2.0549
L_{10}	x_1x_4	−0.08033	x_2x_3	0.40510
L_{11}	x_1x_5	−0.19819	x_2x_4	0.85001
L_{12}	x_1x_6	−0.00455	x_3^2	0.01298
L_{13}	x_2^2	0.0000176	x_3x_4	−0.04761
L_{14}	x_2x_3	−0.000111	x_4^2	0.09303
L_{15}	x_2x_4	0.00109		
L_{16}	x_2x_5	0.00119		
L_{17}	x_2x_6	−0.000171		
L_{18}	x_3^2	0.00191		
L_{19}	x_3x_4	0.00206		
L_{20}	x_3x_5	0.00241		
L_{21}	x_3x_6	−0.000185		
L_{22}	x_4^2	0.07308		
L_{23}	x_4x_5	−0.17266		
L_{24}	x_4x_6	0.000127		
L_{25}	x_5^2	0.09242		
L_{26}	x_5x_6	0.00225		
L_{27}	x_6^2	−0.00000652		

APPENDIX A

PLACE NAMES

The place names used in the papers presented in this report generally follow the new system (Pinyin System) of spelling and hence are different from the names used on most currently available maps. To assist readers in identifying locations, we have compiled the following list of place names which appear in the papers. In each instance the first name is in accord with the new system, and then various earlier spellings and names are given in parentheses.

Anshan: city in Liaoning Province, 30 miles north of Haicheng, population 1.5 million.

Beijing (Peking; Peiping): capital city of China, 100 miles from the sea at Bohai Bay; population 7.5 million.

Bohai Bay (Po Hai; Gulf of Chihli): bay opening into the Yellow Sea.

Daguan (Takuan): city in northeast arm of Yunnan Province.

Haicheng (Haich'eng; Haichen): city in Liaoning Province, 350 miles east-northeast of Beijing.

Hangu (Hanku): coastal city in Hebei Province, 40 miles southwest of Tangshan.

Harbin (Haerhpin): capital city of Heilongjiang Province; population 2.8 million.

Hebei (Hopeh): province in northern China.

Heilongjiang (Heilungkiang): province in northern China.

Henan (Honan): province in east-central China.

Laoting (Lot'ing): city in Hebei Province, 40 miles southeast of Tangshan.

Liaoning: province in northern China.

Longling (Lungling): city in western Yunnan Province.

Luhuo (Luho): city in western Sichuan Province.

Ningho: city in Hebei Province, 30 miles southwest of Tangshan.

Ningxia (Ningsia): province in north-central China.

Qinhuangdao (Ch'inhuangtao): coastal city in Hebei Province, 80 miles east-northeast of Tangshan; population 0.4 million.

Sichuan (Szechwan; Szechuan): province in western China.

Songpan (Sungp'an): city in north-central Sichuan Province.

Tanggu (T'angku; Sinkang): coastal city in Hebei Province, 50 miles southwest of Tangshan.

Tangshan (T'angshan): city in Hebei Province, 100 miles east of Beijing; population 1.0 million.

Tianjin (T'ienching; Tientsin): capital city of Hebei Province, 80 miles southeast of Beijing; northern terminus of the 1200 mile Grand Canal (Yun Ho); major trading center; population 4.5 million.

Tonghai (T'unghai): city in eastern Yunnan Province.

Xingtai (Hsingt'ai; Shintai): city in Hebei Province, 230 miles southwest of Beijing.

Yingkuo (Yinkou): city in Liaoning Province, 30 miles southwest of Haicheng; population 0.2 million.

Yunnan: province in southwestern China.

APPENDIX B

CHINESE INTENSITY SCALE *

Intensity	Type of Observation	Description of Effect
I	Response of buildings.	No damage.
	Response of other structures.	No damage
	Ground surface phenomena.	No response.
	Other phenomena.	Not felt. Tremor is recorded by sensitive seismographs.
II	Response of buildings.	No damage.
	Response of other structures.	No damage.
	Ground surface phenomena.	No response.
	Other phenomena.	Felt by individuals who are very sensitive and at rest.
III	Response of buildings.	No damage.
	Response of other structures.	No damage.
	Ground surface phenomena.	No response.
	Other phenomena.	Felt indoors by people at rest. Vibrations like the passing of a truck. Slight swinging of hanging objects noticed by attentive observers.

*Earthquake Engineering and Hazards Reduction in China, Committee on Scholarly Communication with the People's Republic of China, Nat'l Academy of Sciences, Washington, DC, 1980, Paul C. Jennings, Editor.

Intensity	Type of Observation	Description of Effect
IV	Response of buildings.	Doors, windows, and ceilings with paper make slight creaking sounds.
	Response of other structures.	No damage.
	Ground surface phenomena.	No response.
	Other phenomena.	Felt indoors by most people and outdoors by a few. A few people awakened. Hanging objects swing. Liquids in vessels slightly disturbed. Unstable vessels near to each other clink.
V	Response of buildings.	Doors, windows, wooden floors, ceilings, and joints of wood frame houses creak slightly. Open doors and windows swing back and forth. Dust disturbed. Minor cracks in plaster and plaster dust visible.
	Response of other structures.	No damage.
	Ground surface phenomena.	Small water waves in pools.
	Other phenomena.	Felt indoors by most persons and outdoors by a majority. Most people awakened. Domestic animals become uneasy. Hanging objects swing noticeably. Pendulum clocks stop. Small amounts of liquid spill from well-filled containers. Unstable objects overturn or topple from shelves.
VI	Response of buildings.	Moderate damage in many class I buildings but few seriously damaged. Poorly built houses and sheds may collapse. Slight damage in many class II and III buildings, but few class II buildings moderately damaged.
	Response of other structures.	Slight damage to memorial monuments, masonry towers, and garden walls.
	Ground surface phenomena.	In isolated cases, minor fissures in wet or loose ground. A small number of landslides, earthslumps, and sink holes in mountainous regions.

Intensity	Type of Observation	Description of Effect
VI (cont.)	Other phenomena.	Many run outdoors and stand with difficulty. Domestic animals run out of their stalls. Liquids in containers seriously disturbed and spilled. Some books and objects on shelves overturned or fall. Light furniture may move.
VII	Response of buildings.	Moderate damage to most class I buildings, many seriously damaged, and a few collapse. Moderate damage to most class II buildings; a few seriously damaged. Slight damage to most class III buildings and some moderate to serious damage.
	Response of other structures.	Serious damage to a few garden walls and some may collapse if not well built. Moderate damage to well-built garden walls. Moderate damage at many locations and serious damage at some locations in city walls that are not well built. Moderate damage in some locations in well-built city walls. A few parapet walls collapse. Memorial monuments, masonry towers, and factory stacks may be moderately damaged. Slight damage in many stone pillars and monuments. Open caves in loess blocked by slides. Minor cracks in isolated cases in roads. Occasional slumps in earth embankments, newly built road, and dikes.
	Ground surface phenomena.	Minor fissures in dry ground in some locations. Many large cracks in wet and loose ground. Sandblows in some locations. Slides on steep slopes in isolated cases. Moderate amount of landslides and slumps in mountainous regions, particularly in loose soils. A change may be seen in the flow of springs or level of water table.
	Other phenomena.	People are frightened and run out of doors. May be felt by motor car drivers. Hanging objects swing violently and may fall. Light furniture may move. Books and objects on shelves fall.
VIII	Response of buildings.	Serious damage to most class I buildings, may collapse. Serious damage to many class II buildings, a few collapse.

Intensity	Type of Observation	Description of Effect
VIII (cont.)		Moderate damage to most class III buildings, a few seriously damaged or collapse.
	Response of other structures.	Serious damage and partial collapse in poorly built garden walls. Some serious damage in well-built garden walls. Serious damage at many locations and collapse at some locations in city walls that are not well built. Many parapet walls collapse. Serious damage at some locations in firm city walls. A few masonry parapet walls collapse. Many memorial monuments damaged. Moderate damage in masonry towers and factory stacks, some with serious damage or collapse if not well built. Unstable stone pillars or monuments displaced or overturned. Moderate damage to many stable monuments, some overturned. Moderate slumps on steep road embankments or cuts. Serious damage to underground pipelines in isolated cases.
	Ground surface phenomena.	Cracks of several centimeters in firm ground. Cracks greater than 10 cm on loose soil slopes and wet riverbanks. Sand and mud boils in regions of shallow water table. Considerable sliding and slumping in regions of broken rock or loose soil, which may block rivers and form new pools. Wells may dry up or new springs may occur.
	Other phenomena.	People stand with difficulty. People and animals injured in damaged buildings. Furniture displaced and may overturn.
IX	Response of buildings.	Most class I buildings collapse. Many class II buildings collapse. Serious damage and some class III buildings collapse.
	Response of other structures.	Most poorly built garden walls collapse. Serious damage and partial collapse in well-built garden walls. Serious damage at many locations in well-built city walls. Collapse of many parapets. Serious damage to memorial monuments. Serious damage and some collapse of many

Intensity	Type of Observation	Description of Effects
IX (cont.)		masonry towers and factory stacks. Many stable stone pillars and monuments overturned. Cracks in roads and embankments. Rails bent locally. Breaks and damage in underground pipelines.
	Ground surface phenomena.	Many cracks about 10 cm wide in soil. Cracks of tens of cm cross each other and extend for great lengths on loose sediments and slopes of river banks. Many landslides and earth slumps. Well water dries up or new springs occur in many locations.
	Other phenomena.	Furniture overturned and damaged.
X	Response of buildings.	Collapse of many class III buildings.
	Response of other structures.	Serious damage in many monuments. Masonry towers and factory stacks collapsed. Stable stone pillars and monuments overturn. Embankments and dikes destroyed. Roads deformed and extensively cracked. Underground pipelines broken.
	Ground surface phenomena.	Several-centimeter wide cracks in ground, some 1-m wide in isolated cases. In sediments, cracks may form wide bands and extend for several kilometers. Cracks occur in rock in isolated cases. Slides occur on steep slopes in mountainous regions and riverbanks. Many earthslumps in loose soils. Water waves splash the banks of rivers and pools.
	Other phenomena.	Furniture and other objects indoors damaged.
XI	Response of buildings.	Buildings destroyed, generally.
	Response of other structures.	Embankments and dikes destroyed, generally. Rails bent in many areas. Underground pipelines out of service, generally.
	Ground surface phenomena.	Many broad cracks formed on ground with a great amount of loose and saturated sediment ejected from cracks in some cases. Numerous landslides and slumps.

Intensity	Type of Observation	Description of Effects
XI (cont.)		Considerable horizontal and vertical surface faulting. Surface water and underground water table changed significantly.
	Other phenomena.	Many people, domestic animals, and property buried in collapse of buildings.
XII	Response of buildings.	Buildings destroyed in an extensive region.
	Response of other structures.	Other structures destroyed, generally.
	Ground surface phenomena.	Significant topographic changes in an extensive region. Serious surface water and underground water table changes in an extensive region.
	Other phenomena.	Animals and crops destroyed from the effects of landslides and slumps in mountainous regions.