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AN ASSESSMENT OF EARTHQUAKE RESPONSE CHARACTERISTICS AND DESIGN PROCEDURES FOR PORT AND HARBOR FACILITIES

by

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Information regarding the behavior of port and harbor facilities during earthquakes is presented and the procedures used for the seismic design and analysis of such facilties are considered. It is noted that most of the observed major earthquake-induced damage to port and harbor facilities has resulted from large-scale liquefaction and/or sliding of the loose, saturated, cohesionless soil materials that are prevalent in and around port and harbor facility sites. Even when complete liquefaction and/or sliding have not occurred, the soil deposits and backfill materials in the vicinity of port and harbor facilities have often undergone significant earthquake-induced deformations that have caused substantial damage. Structure-specific design considerations for quay walls, sheet-pile bulkheads, piers, and pile supports are summarized. Dynamic analysis techniques are shown to provide an important means for enhancing facility designs and seismic design provisions.

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AN ASSESSMENT OF EARTHQUAKE RESPONSE CHARACTERISTICS AND DESIGN PROCEDURES FOR PORT AND HARBOR FACILITIES

by

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ABSTRACT

Prior experience has shown that port and harbor facilities have often undergone substantial damage and destruction during major earthquakes, with resulting serious regional and national economic consequences. This paper addresses this problem through a compilation and assessment of available information regarding the behavior of port and harbor facilities during prior earthquakes, and the procedures used for the seismic design and analysis of such facilities. The importance of carefully considering the earthquake response characteristics of the loose, saturated, cohesionless soil deposits that typically prevail at port and harbor sites is clearly shown, along with the need for certain improvements in current seismic design and analysis procedures.

INTRODUCTION

It is well known that port and harbor facilities are particularly susceptible to the effects of strong earthquakes. The widespread failures of such facilities that have occurred during prior earthquakes, and the corresponding major interruptions of port operations for extended periods of time, have resulted in serious hardships and economic consequences for the stricken areas. In view of this, it is important to gain insight into the earthquake-induced behavior of port and harbor facilities, so that these damaging effects can be minimized in the future.

With this as background, a multiyear research program is being conducted to investigate the seismic response characteristics of port and harbor facilities (AA, 1980). An important part of this program has involved the compilation and assessment of the considerable, but widely scattered, information generated by engineers throughout the world regarding (a) how port and harbor facilities have fared during prior earthquakes; and (b) how such facilities have been designed and analyzed to resist earthquake-induced phenomena. This paper summarizes this compilation and assessment.

BEHAVIOR DURING PRIOR EARTHQUAKES

Table 1 provides a summary of damage induced to port and harbor facilities during prior earthquakes and our best interpretation of available information regarding possible causes of this damage. Most of the information on which Table 1 is based has been obtained from Japan, with

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TABLE 1. SUMMARY OF EARTHQUAKE-INDUCED DAMAGE TO PORT AND HARBOR FACILITIES

Earthquake			Damage		
Location	Date	Magnitude	Port Location	Description	Possible Cause(s)
Kanto, Japan	Sep 1, 1923	8.2	Yokohama and Yokosuka	Concrete block quay walls: sliding, tilting, and/or collapse with some bearing capacity failure of rubble-stone foundation Steel bridge pier: buckling of pile supports	A C,E
Kitaizu, Japan	Nov 26, 1930	7.0	Shimizu	Caisson quay wall (183 m long): tilting, outward sliding (8.3 m), and settlement (1.6 m) L-Shaped block quay wall (750 m long): outward sliding (4.5 m) and settlement (1.2 m)	A,B,C
Shizuoka, Japan	Jul 11, 1935	6.3	Shimizu	Caisson quay wall: outward sliding (5.5 m) and settlement (0.9 m) accompanied by anchor system failure	A,B,C
Tonankai, Japan	Dec 7, 1944	8.3	Yokkaichi Nagoya Osaka	Pile-supported concrete girder and deck: outward sliding (3.7 m) accompanied by extensive soil sliding Sheet-pile bulkhead with platform: outward bulging (4 m) Steel sheet-pile bulkhead: outward bulging (3 m)	A,B,C
Nankai, Japan	Dec 21, 1946	8.1	Nagoya Yokkaichi Osaka Uno	Sheet-pile bulkhead with platform: outward bulging (4 m) Pile-supported concrete girder and deck: outward sliding (3.7 m) Steel sheet-pile bulkhead: outward bulging (3 m) and settlement (0.6 m) Gravity-type concrete block and caisson quay wall: seaward sliding (0.4 m) accompanied by soil sliding	A,B,C
Tokachi-Oki, Japan	Mar 4, 1952	8.1	Kushiro	Concrete caisson quay wall: tilting, outward sliding (6 m), and settlement (1 m)	A,B,C
Chile	May 22, 1960	8.4	Puerto Montt Talcuhuano	Concrete caisson quay walls: overturning and extensive tilting Steel sheet-pile seawall: outward sliding (up to 1 m) and anchor failure Gravity-type concrete seawall: complete overturning and sliding (1.5 m) Concrete block quay wall: outward tilting	B,C A
Alaska	Mar 27, 1964	8.4	Anchorage Valdez Whittier Seward Kodiak	Dock structures: extensive seaward tilting with bowing, buckling, and yielding of pile supports Entire harbor: destroyed by massive submarine landslide Pile-supported piers and docks: buckling, bending, and twisting of steel pile supports Steel sheet-pile bulkhead: extensive bulging Major portion of harbor: destroyed by massive submarine landslide Seawalls: extensive settlement (up to 5 m) from tectonic effects and foundation failures	B,D,E B,D B,D B,D B,D B,D

TABLE 1. (CONCLUDED)

Earthquake			Damage		
Location	Date	Magnitude	Port Location	Description	Possible Cause(s)
Niigata, Japan	Jun 16, 1964	7.5	Niigata	Extensive damage due to liquefaction and sliding of soil strata. Sampling of damage is as follows: Gravity type retaining walls: settlement (up to 4 m) and tilting Piers and landings: sliding (up to 5 m), submergence, and tilting Sheet-pile bulkheads: sliding (over 2 m), submergence, settlement (up to 1 m), and tilting. Extensive anchor failure Quay-walls: outward sliding (up to 3 m) and settlement with extensive anchor failure	B,C
Tokachi-Oki, Japan	May 16, 1968	7.8	Hachinohe	Steel sheet-pile bulkheads: outward sliding (0.9 m), tilting, and settlement, with anchor failure	A
			Aomori	Gravity-type quay wall: sliding and settlement (0.4 m)	
				Gravity-type breakwater: sliding (0.9 m) and pavement settlement (0.9 m)	A
			Hakodate	Steel sheet-pile bulkhead: seaward tilting (0.6 m) and apron settlement (0.3 m) Quay-wall: settlement (0.6 m) and sliding (0.4 m)	B
Nemuro-Hanto-Oki, Japan	Jun 17, 1973	7.4	Hanasaki	Gravity-type quay wall: sliding (1.2 m) and settlement (0.3 m) with corresponding apron settlement (1.2 m) Steel sheet-pile bulkhead: sliding (2 m) and anchor failure	B
			Kiritappu	Steel sheet-pile bulkhead: relatively minor damage Gravity-type quay walls: relatively minor damage	B
Miyagi-Ken-Oki, Japan	Jun 12, 1978	7.4	Shiogama	Concrete gravity-type quay wall: outward tilting (0.6 m) and apron pavement settlement (0.4 m)	A
			Ishinomaki	Steel sheet-pile bulkheads: outward sliding (up to 1.2 m) and apron settlement (up to 1 m)	
				Concrete block retaining wall: sliding, tilting, and cracking with corresponding pavement settlement (0.2 m) relative to wall	B
			Yuriage	Concrete block gravity quay wall: headwork displacement (1.2 m) and apron settlement (0.3 m)	A

Legend

A: Excessive lateral pressure from backfill materials, in the absence of complete liquefaction, and possibly accompanied by reduction in water pressure on outside of wall
B: Liquefaction
C: Localized sliding
D: Massive submarine sliding
E: Vibrations of structure

additional data from the United States (Alaska) and from Chile. This table shows the extensive earthquake-induced damage that has been imparted to ports and harbors. For example, quay walls and sheet-pile bulkheads have undergone substantial lateral sliding, bulging, and tilting with corresponding anchor system failures and extensive settlement and cracking of paved aprons. Docks and piers have undergone extensive sliding and buckling, bending, and yielding of pile supports (Duke and Leeds, 1963; Okamoto, 1973; NAS, 1973; Noda and Uwabe, 1975; JSCE, 1980).

Evaluation of these data indicates the following trends:

- Most of the observed major earthquake-induced damage to port and harbor facilities has resulted from large-scale liquefaction and/or sliding of the loose, saturated, cohesionless soil materials that are prevalent in and around port and harbor facility sites.

- Even when complete liquefaction and/or sliding have not occurred, the soil deposits and backfill materials in the vicinity of port and harbor facilities have often undergone significant earthquake-induced deformations that have caused substantial damage to these facilities. For retaining wall structures, these deformations have resulted in extensive lateral pressure buildup behind the walls and, in some cases, have been accompanied by a reduction in water pressure outside of the walls (Seed and Whitman, 1970).

- There is little evidence of earthquake-induced damage to port and harbor facilities due directly to the vibrations of the structures themselves. This may be due to the following possibilities: (1) any damage that may occur due to structural vibrations has been overshadowed by the effects of the large-scale soil instabilities that have occurred in the past; or (2) it may indeed be that the seismic design provisions for structural vibrations are conservative for the conditions represented by the earthquake observations. Detailed investigations of the earthquake-induced behavior of port and harbor facility structures and sites, using dynamic analysis techniques, could provide important insights along these lines.

- The most complete and comprehensive documentation of earthquake-induced effects on port and harbor facility structures has been compiled by the Japanese, with only scant information available in the United States (except for Alaska) and the rest of the world. However, even the documented information from Japan is insufficient to provide a complete basis for assessing causes of earthquake-induced damage to port and harbor facility structures. For additional assessments of this type from future earthquakes, more information is needed regarding dynamic soil property measurements at the harbor sites, and measured vibratory responses of the structures and the adjacent soil deposits.

SEISMIC DESIGN PROCEDURES

The current practice regarding the seismic design of port and harbor facilities is being investigated through review of design procedures from Japan (e.g., JSCE, 1980), agencies of the United States government (e.g., USN, 1968-1971; DANAF, 1973), and port and harbor authority personnel and consulting engineers engaged in the design of port and harbor facilities. This practice is summarized below in terms of general geotechnical considerations, and structure-specific considerations for quay walls, bulkheads, piers, and piles.

GENERAL GEOTECHNICAL CONSIDERATIONS

Table 2 summarizes the results to date of our survey pertaining to the current practice in Japan and the United States for considering the following geotechnical phenomena: (1) earthquake-induced lateral earth pressures for retaining wall structures; (2) earthquake-induced dynamic water pressures; (3) earthquake effects on bearing capacity; (4) lateral and axial resistance of piles to seismic effects; (5) earthquake-induced slope instability; and (6) liquefaction. This table indicates that most of these phenomena either are ignored or are treated using simplified pseudo-static procedures. Dynamic analysis is now routinely carried out only for liquefaction investigations; however even this is a relatively recent development, and a potential major problem exists at many ports and harbors because possible liquefaction had been essentially ignored in past seismic design practice. In fact, when viewed in the context of the overall design requirements for port and harbor facilities, the geotechnical-related seismic effects listed in Table 2 do not play nearly as major a role in the design process as might be expected from the extensive damage induced to such facilities by prior earthquakes.

Further discussion of the geotechnical aspects of seismic design practice pertaining to lateral earth pressures and slope instability is given in the following paragraphs. Discussion of procedures for evaluating liquefaction potential is provided in the subsequent section of this paper that deals with dynamic analysis techniques.

Lateral Earth Pressures for Retaining Wall Structures. The Mononobe-Okabe equation is the predominant method used to define earthquake-induced lateral pressures for quay walls, sheet-pile bulkheads, and other port and harbor retaining wall structures (Mononobe, 1929; Okabe, 1926). As discussed by Seed and Whitman (1970), this approach assumes that (1) the wall moves sufficiently to mobilize the minimum active pressure; (2) when the minimum active pressure acts against the wall, a wedge-shaped soil mass is at the point of incipient failure with the maximum shearing resistance mobilized all along the plane sliding surface; and (3) the soil wedge acts as a rigid body with earthquake accelerations acting uniformly throughout the wedge. Based on these assumptions, Mononobe and Okabe used the Coulomb sliding wedge method to obtain an expression for the total pseudo-static horizontal earthquake force as a function of the horizontal and vertical ground accelerations, and various parameters related to the soil, wall, and backfill. Seed and Whitman (1970) evaluated the sensitivity of the Mononobe-Okabe equation to these parameters and, from this, developed a simplified form of this equation. It is noted that the Mononobe-Okabe equation, while generally considered to be adequate for retaining walls and dry or moist soils above the water table, does not consider the increased lateral pressures that may be applied to quay walls and bulkheads below the water table.

Earthquake-Induced Slope Instability. At port and harbor sites, the potential for earth-induced slope instability is invariably evaluated using

TABLE 2. GEOTECHNICAL-RELATED SEISMIC DESIGN PRACTICE FOR PORT AND HARBOR FACILITIES

Item	Predominant Design Practice
Earthquake-Induced Lateral Earth Pressures for Retaining Wall Structures	Mononobe-Okabe method most typically used, occasionally incorporating suggested simplifications by Seed and Whitman (1970).
Earthquake-Induced Dynamic Water Pressures	Usually ignored. Westergaard (1933) procedure occasionally used.
Earthquake Effects on Bearing Capacity	Usually assume no seismic effect.
Lateral and Axial Resistance of Piles to Seismic Effects	Usually not considered.
Earthquake-Induced Slope Instability	Pseudo-static methods most typically used.
Liquefaction	Standard procedures described by Seed (1979a) most typically used, incorporating empirical and/or 1-D total stress dynamic analysis techniques. Occasional use of 1-D effective stress methods.

pseudo-static methods. In this approach, the stability of a potential sliding mass is determined as for static loading conditions, and earthquake effects are accounted for by including an additional pseudo-static horizontal force acting on the sliding mass. This additional force is expressed as the product of the weight of the sliding mass under consideration and a seismic coefficient that is normally based on the seismicity of the region. Typically, these seismic coefficients range from 0.1 to 0.15. Prior applications have shown that this method can be useful in evaluating the performance of embankments constructed of soils that do not lose significant strength during earthquakes (e.g., clays or clayey soils, dry or moist or extremely dense cohesionless soils); however, there is substantial evidence that the pseudo-static approach does not have the capability to predict potential earthquake-induced slope failures for the loose, saturated, cohesionless soils that typically exist at port and harbor sites and have a tendency to lose strength due to porewater pressure buildup and liquefaction during strong ground shaking (Seed, 1979b).

STRUCTURE-SPECIFIC CONSIDERATIONS

A brief summary of structure-specific design considerations for quay walls, sheet-pile bulkheads, piers, and pile supports is given in the paragraphs that follow.

Quay Walls--External seismic forces considered in the design of quay walls are lateral earth pressure, water pressure, and the inertial force of the wall itself. Gravity-type quay walls are designed to avoid overturning and excessive tilting or sliding, although some wall movement is tolerated; however, bearing capacity failure due to inertial forces and tilting induced by lateral seismic forces, which has in the past led to slip failures in the soil, is seldom considered. In general, block-type quay walls are more susceptible to seismic effects than caisson-type quay walls; they are particularly vulnerable to earthquake-induced sliding between layers of blocks, which is seldom addressed in current design practice.

Sheet-Pile Bulkheads--The design of sheet-pile bulkheads for seismic effects typically addresses the sheet pile cross-sectional properties and length, the tie rods, and the anchor system. In this, experience from past earthquakes shows that the principal earthquake-induced failure mode of sheet-pile bulkheads has been insufficient anchor resistance. This has been caused by the fact that such anchor systems have generally been installed at shallow depths where soils are most susceptible to a loss of strength from porewater pressure buildup and liquefaction. Therefore, the design of anchor systems is particularly important, and may be enhanced through the use of deeply embedded piles and/or sheet piles.

Piers--When compared to quay walls and sheet-pile bulkheads, piers have suffered much less extensive damage during prior earthquakes. This is because piers, which are aboveground and are constructed of piles with platform decks for landing purposes, are relatively lightweight and are not subjected to lateral soil pressures of the type applied to quay walls and bulkheads. The seismic design of pier structures is typically based on pseudo-static lateral forces, computed in a manner analogous to that for conventional buildings (e.g., UBC, 1979).

Piles--Piles are widely used foundation support elements, not only for piers but for bulkheads and quay walls as well. Past design practice has seen the wide use of batter piles, in addition to vertical piles, presumably to provide a greater stiffness in resisting the lateral loads that might be encountered during the structure life. However, experience from prior earthquakes has shown that the configuration and large lateral stiffness of batter piles has caused severe damage to pile caps and decking of pier structures (NAS, 1973; Margason, 1975). For this reason, vertical piles, which have a greater lateral flexiblity, are now preferred over batter piles in current seismic design practice. Design considerations for vertical piles are: (1) their embedment depth should be sufficient to provide for nearly complete end fixity, to be consistent with assumptions commonly made when designing such piles; and (2) it is vital to address the possible effects of porewater pressure buildup and liquefaction of the soil strata at port and harbor sites--which reduce the effective embedment depth of the piles and increase the lateral loads applied to the piles. Group action of adjacent vertical piles, which would reduce the effective lateral stiffness of a single pile in the group, is seldom considered in current design practice.

DYNAMIC ANALYSIS TECHNIQUES

Dynamic analysis techniques, although not widely used in past designs of port and harbor facilities, can provide an important means for enhancing facility designs and seismic design provisions. When used with sound engineering judgment, such techniques can provide an improved basis for evaluating earthquake-induced structure motions and stresses, effects on bearing capacity, lateral earth pressures, and potential slope instabilities--including effects of soil/structure interaction and possible porewater pressure buildup and liquefaction of the soil deposits at the port and harbor facility sites. In this context, two methods--total stress methods and effective stress methods--are discussed in the paragraphs that follow.

TOTAL STRESS METHODS

Total stress methods involve the use of dynamic analyses that compute the total state of stress in the soil and backfill (Seed, 1979a, b). Such methods, as applied to port and harbor facility soil/structure systems, would involve the following steps: (1) use of a suitable dynamic analysis technique to compute the response of the soil/structure system to the expected earthquake motions at the port and harbor facility site; (2) conversion of the resulting shear stress time histories in the soil into a series of equivalent uniform stress cycles; and (3) assessment of the liquefaction potential of the site, through comparison of the computed earthquake-induced cyclic stresses (from Step 2) to the cyclic stresses shown by laboratory tests and/or empirical methods to lead to liquefaction of the soil medium. In Step 1, the dynamic analysis technique used would most typically involve existing two-dimensional (or three-dimensional) finite element codes that utilize equivalent-linear (e.g., Lysmer et al., 1975) or nonlinear soil models (e.g., Bathe, 1978) to compute the soil and structural response including soil/structure interaction effects and the geometry of the site soil deposits. Analyses using such techniques may be supplemented or preceded by separate computations of free-field response using one-dimensional techniques (e.g., Schnabel et al., 1972) for site geometries that can be considered to be comprised of horizontal soil layers of infinite extent subjected to vertically propagating shear waves. In Step 2, the conversion of the resulting irregular soil stress histories to equivalent cyclic stresses can be carried out using statistical procedures (e.g., Seed and Idriss, 1969; Donovan and Singh, 1978).

Once the cyclic soil stresses induced by the earthquake are obtained as indicated above, it remains in Step 3 to assess the liquefaction potential of the site. To do this, it is necessary to determine the critical cyclic stresses that result in liquefaction of the soil medium, and to compare these critical stresses to the earthquake-induced stresses. This can be done using established cyclic laboratory test procedures as described by Seed (1979a). However, because data from such tests are prone to uncertainties from sample disturbance, the use of results from empirical methods has also been advocated. Such methods (e.g., Seed and Idriss, 1981) utilize an extensive body of field observations of the occurrence or nonoccurrence of liquefaction during actual earthquakes to establish critical combinations of cyclic stress ratio and Standard Penetration Test (SPT) resistance of the soil that represent lower bound conditions for the onset of liquefaction over a range of earthquake magnitudes.* Regardless of whether laboratory tests or empirical methods (or both) are used to define the critical cyclic stresses, care must be taken to interpret the uncertainties that arise either from sample disturbance (in the case of the laboratory tests) or from the use of SPT blowcounts to characterize the liquefaction resistance of the soil (in the case of the empirical methods).

Total stress methods, as summarized above, have been successfully and widely used to analyze the response of earth dams and embankments, and are applicable to port and harbor facilities as well. In fact, these methods represent the only approach now available for carrying out structural and soil response analyses that incorporate soil/structure interaction and the complete range of complex site geometries that might exist at port and harbor sites (AA, 1976). However, a limitation of total stress methods is that the dynamic analysis techniques used to compute the earthquake-induced

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*As used in these empirical methods, the cyclic stress ratio is defined as the ratio of the earthquake-induced cyclic stress to the initial vertical effective stress acting on the soil layer before the cyclic stresses were applied. The SPT resistance correponds to blowcounts corrected to an effective vertical stress of 1 tsf.

response (under Step 1) do not fully incorporate the potential effects of the buildup of porewater pressure. In recognition of this, some investigators have advocated a progressive analysis in which, over successive time segments of the ground shaking, states of soil stress from the prior time segment are used as input to separate computations of porewater pressures; these pressures, in turn, are used to modify the dynamic soil properties to be considered over the next time segment of the analysis.

EFFECTIVE STRESS METHODS

Effective stress methods are based on the fundamental premise that the deformations of the soil deposits are controlled by the effective stresses. Such methods involve the use of a soil material model that incorporates nonlinear stress/strain behavior together with a mechanism for predicting porewater pressure generation and dissipation (e.g., Martin and Seed, 1978a,b; Lee and Finn, 1978). Effective stress methods involve the following steps: (1) use of laboratory tests of the soil specimens to determine the material parameters for the effective stress soil model; and (2) a dynamic analysis of the soil deposit that utilizes these measured material parameters and the estimated seismic input motions to compute the response of the soil deposit including porewater pressure buildup and dissipation. An attractive feature of the effective stress methods is that the effects of porewater pressure dissipation during earthquake shaking can be included in the analysis. In many waterfront structures, the geometry is such that drainage paths are relatively shorter than, for instance, large earth dams and it is therefore more important that the effects of dissipation of porewater pressure, as well as the buildup of porewater pressure, be considered.

Effective stress methods, as summarized above, are now primarily available only as one-dimensional (1-D) procedures for analyzing liquefaction potential under free-field conditions, for sites comprised of horizontal soil layers and subjected to vertically propagating shear waves. For port and harbor sites that can be represented in this manner, such analyses can indeed be valuable, particularly in view of the potential importance of porewater pressure effects at such sites, as discussed above. However, because of their basic availability only as 1-D procedures, effective stress methods cannot be used for structural and soil response analyses that incorporate soil/structure interaction and the full range of complex port and harbor site geometries that might be encountered; such analyses require two-dimensional (2-D) or three-dimensional (3-D) procedures.

The extension of existing effective stress methods to accommodate the above 2-D or 3-D situations is not a simple matter, although work to develop such methods is being carried out (e.g., Ferritto, 1982; Pyke, 1982). This work should contribute substantially to our understanding of the earthquake-induced response of port and harbor structures, as well as other structures (e.g., earth dams) for which porewaterp ressure effects may be important. However, it should be noted that, while it is desirable to develop effective stress methods in this way for <u>future</u> seismic design applications, it is important for <u>present</u> applications to at least recognize the potential effects of liquefaction and the other earthquake-induced phenomena that may occur at port and harbors, and to consider these effects through the use of the best available dynamic analysis techniques combined with sound engineering judgment.

SUMMARY AND CONCLUSIONS

The findings of the investigation reported herein are as follows:

- Earthquake Damage--The earthquake-induced damage to port and harbor facilities has often been very severe and even catastrophic at sites where large-scale liquefaction and/or submarine sliding have occurred. However, even when liquefaction or sliding have not taken place, earthquake-induced deformations of backfill and underlying soils with low penetration resistance have caused significant damage to port and harbor facilities.

- Seismic Design Provisions--Seismic effects are often not nearly as important a design consideration for port and harbor facilities as might be expected from the extensive damage to such facilities that has occurred during prior earthquakes. The seismic design provisions that do exist, typically address some of the potential earthquake-induced phenomena in a simplified pseudo-static manner and ignore many of the others. Dynamic analysis, which is now routinely used only for liquefaction assessments, should be incorporated to a much greater extent into seismic design provisions for port and harbor facilities.

- Dynamic Analysis Techniques--Total stress methods represent the only methods currently available for analyzing the seismic response of port and harbor structures, backfill, and soil deposits--including soil/structure interaction and the full range of site geometries that might be encountered at port and harbor facility sites. However, a limitation of such methods is that the computation of earthquake-induced stresses on which the liquefaction evaluation is based does not fully include the potential effects of porewater pressure buildup. Effective stress methods, which consider porewater pressure buildup and dissipation during the ground shaking, are presently only 1-D, and are therefore suitable only for free-field liquefaction analyses involving horizontally layered soil sites subjected to vertically propagating shear waves. The future development of 2-D or 3-D effective stress methods could be a fruitful direction of research for enhancing our ability to design port and harbor facility structures to resist earthquake effects.

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