Coastal Dynamics during Earthquakes

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ABSTRACT

The results of research on some aspects of coastal dynamics during earthquakes, carried out in the Institute of Hydro-Engineering, are summarized. The attention is focused on the liquefaction-related phenomena, like modeling the earthquake-induced generation of pore-pressures and subsequent liquefaction of subsoil, the behavior of liquefied soil, underwater landslides, sinking of structures in a liquefied seabed and large displacements of quay-walls.

1. INTRODUCTION

The coastal zone is a very complex system characterized by various interactions between the sea, shore-line, seabed and the infrastructure. The dynamics of such a system can be analyzed at various time and space scales, depending on the aim of investigations. In this paper, the attention will be focused on the problems which appear in the coastal zone due to earthquakes, i.e. during a very short period of time. The main threat to the coastal zone comes from the earthquake-induced soil liquefaction, which causes submarine landslides, sinking and displacements of structures, floatation of submarine pipelines, changes of seabed morphology etc. The phenomenon of liquefaction and associated catastrophic events have already led to economic losses measured in billions, also costing thousands of lives. Therefore, the research on the above mentioned problems is important as it may lead to elaboration of effective countermeasures.

Liquefaction is the phenomenon which transforms macroscopically solid saturated soil into a mixture that behaves like a viscous fluid. Liquefaction is caused by the shear stresses that develop in the soil skeleton due to seismic excitations, explosions, vibrations, water waves etc. Liquefaction is preceded by the phenomenon of generation of excess pore-pressures and subsequent reduction of effective stresses in the soil skeleton. As a consequence of the phenomenon of pore-pressure generation, the macroscopic mechanical properties, as those defined by the shear modulus, deteriorate, and finally the saturated soil liquefies. After the earthquake, the process of dissipation of excess pore-pressures takes place and the saturated soil becomes more and more solid, up to nearly initial geostatic state.

The research on mechanics of liquefaction and associated phenomena has been carried out, in the Institute of Hydro-Engineering, for more than 20 years. The basic results are summarized in the state-of-the-art article by Sawicki & Mierczyński (2006), where also the most important publications, dispersed in the world literature, are discussed. We have proposed a theory of liquefaction, using applied mechanics methods, and have shown how this theory can be applied to analyze various problems of engineering importance, including coastal dynamics during earthquakes. The recent achievements are summarized in the papers by de Groot et al. (2006), Sumer et al. (2007), Sawicki & Świdziński (2006, 2007), and some others.
Some applications of the methods elaborated in the Institute of Hydro-Engineering deal with the description of devastating effects of the Kocaeli earthquake which took place in 1999, in Turkey, where the coast of Marmara Sea experienced severe damage due to soil liquefaction. It is hoped that our contributions to the field of liquefaction will help in establishing good research contacts with our Taiwanese partners, and that this paper will be a kind of bridge between the soil mechanics society and the coastal engineers.

2. THEORETICAL MODEL OF LIQUEFACTION

In this section, the model of compaction and liquefaction of saturated granular soils, subjected to cyclic loadings will be outlined, Sawicki (1987). The model is defined by the following equations:

\[
\frac{d\Phi}{dN} = D_1 J \exp(-D_2 \Phi), \tag{1}
\]

\[
[\sigma']^{dev} = 2(G_0 + G_i \sqrt{p'})[\varepsilon]^{dev}, \tag{2}
\]

\[
\frac{du}{dN} = \frac{1}{a} \frac{d\Phi}{dN}, \tag{3}
\]

where: \( \Phi \) = irreversible porosity change (compaction); \( N \) = number of loading cycles (continuous); \( J \) = second invariant of the strain tensor; \( p' \) = mean effective stress; \([\sigma']^{dev}\) = deviator of the effective stress tensor; \([\varepsilon]^{dev}\) = deviator of the strain tensor; \( u \) = excess pore pressure, generated by cyclic loading; \( a \) = compressibility of the soil skeleton; \( D_1, D_2, G_0, G_i \) = soil parameters, which should be determined experimentally. The details of the model can be found in the literature cited in this paper.

Eq. (1) describes the compaction of dry or saturated sand, but in free draining conditions, due to cyclic loading. Compaction in fully drained conditions is related to the pore pressure generation in undrained conditions by Eq. (3). Eq. (2) relates the deviators of the strain and effective stress tensors, where \( G_0 + G_i \sqrt{p'} = G \) is the shear modulus. During the generation of excess pore pressure, the mean effective stress decreases, according to the relation \( p' = p - u \), where \( p \) = total mean stress. When \( p' \) decreases, the shear modulus \( G \) also decreases which models the progressive weakening of saturated soil. Liquefaction takes place when \( p' = 0 \), and in this case the shear modulus takes its residual value of \( G_0 \). The system of Eqs. (1–3) is coupled and it describes the modeled phenomena quite well, which has been confirmed by a large number of independent experimental data. The structure of constitutive equations is simple, and the number of material constants is minimal, which is important in engineering applications.

3. APPLICATIONS OF THE MODEL AND ASSOCIATED RESEARCH

The model has been applied to the analysis of various problems of engineering importance which could not be solved using traditional methods. The first group of applications deals with the compaction and settlements of dry or free draining soils. These applications include: settlements of subsoil due to earthquake; settlements of cyclically loaded machine foundations; settlements of embankments and roads due to
traffic; behavior of cyclically loaded piles, settlement of backfills behind quay-walls, etc. The second group of applications deals with the development of excess pore pressure and liquefaction as, for example: behavior of the saturated soil stratum during earthquakes; liquefaction of earth dams; behavior of seabed due to the action of water waves; behavior of seabed beneath marine structures; behavior of saturated soils during explosions, etc. Respective references are quoted in the state-of-the-art article by Sawicki & Mierczyński (2006). Such wide applications show that the model proposed in the Institute could also be an attractive proposition for coastal engineers.

It should be mentioned that each of the above mentioned problems was analyzed using the methods of applied mechanics. This means that the constitutive equations (1-3) were supplemented with general equations dealing with the mass and momentum balances, etc., together with respective initial and boundary conditions. Usually numerical methods, based on the finite difference or finite element methods, were employed to solve the system of governing equations.

The model described in Section 2 has been elaborated for the cyclic loadings. It is known that liquefaction can also be triggered by the monotonic loadings, mainly in the contractive soils. The research on this problem has been carried out, in the Institute of Hydro-Engineering, in recent years. Extensive experimental work has already been done and some models proposed, see Sawicki (2007), Sawicki & Świdziński (2007). This research supplements previous investigations on the compaction/liquefaction model for cyclic loadings.

It should be added that associated research, on the problems related to liquefaction, has also been carried out, including investigations of such phenomena as the pore pressure dissipation and re-solidification of saturated soil after liquefaction, settlements of backfills behind quay-walls after liquefaction, flow of liquefied soil, sinking of structures in the liquefied subsoil, etc.

4. EARTHQUAKE-INDUCED LIQUEFACTION OF SEABED

The most simple application of the liquefaction model deals with the analysis of pore-pressure generation in a saturated soil stratum as, for example, seabed, see Fig. 1. The stratum is resting on a rigid and impermeable bedrock and is subjected to the horizontal ground shaking caused by an earthquake. It is assumed that the seismic excitation is sinusoidal, with given frequency, but the amplitude of subsequent cycles may change. Also the soil properties may vary with the depth. In this case, the equation of motion describes the propagation of shear waves in the seabed. It takes the following simple form, see Sawicki & Świdziński (2007):

\[ \frac{d^2 \tau}{dZ^2} + \frac{\zeta}{G} \tau = 0, \]

where \( \tau \) = non-dimensional shear stress; \( Z \) = non-dimensional vertical co-ordinate; \( \zeta \) = certain coefficient that depends on frequency of excitation, density of saturated soil, depth of a layer, characteristic stress and strain.

The system of equations (1–4), together with respective initial and boundary conditions, enables analysis of the saturated subsoil (seabed) behavior during earthquake. For example, Fig. 2 shows a simulation of the development of excess pore-pressures during the Kocaeli earthquake, see Sawicki & Świdziński (2007). Liquefaction was initiated, at the second loading cycle, at the base of stratum (Fig. 2a) and then had propagated upwards, as shown in Fig. 2b. Recall that the soil liquefies...
when the mean effective stress reaches the zero value. This means that the curve \( u = u(Z, N) \) touches the line \( p_0'(Z, N) \) which represents the distribution of the initial mean effective stress as shown in Fig. 2a. This figure illustrates the upwards propagation of that zone as function of the loading cycles. Nb. the insets to Fig. 2 show the history of the ground horizontal acceleration corresponding to the measured excitations during the Kocaeli earthquake (shown is a kind of random realization).

It can also be shown, in the form of various plots, how the strains and effective stresses change during the stage prior to liquefaction, depending on the excess pore-pressure.

![Seabed subjected to earthquake shaking](image1)

![Development of excess pore pressure and the onset of liquefaction](image2)
5. BEHAVIOR OF LIQUEFIED SOIL

Experimental investigations show that the liquefied soil may be treated macroscopically like a viscous fluid. Two kinds of experiments were performed in the Institute of Hydro-Engineering, and their results show that the dynamic viscosity of liquefied soil is of the order of $\eta = 10^6 \, \text{Ns} / \text{m}^2$. The experiment of the first type was performed in the tri-axial compression apparatus, when the saturated soil sample had liquefied and the steady state reached (steady state flow of liquefied sample at constant volume and constant stresses). The second type of experiment dealt with the sinking of heavy cylinder in the liquefied subsoil. The steel cylinder was placed on the saturated soil, which filled the container placed, in turn, on a kind of shaking table. The sinking of the cylinder in the liquefied subsoil was measured, and on this basis the viscosity determined. The details of those investigations are presented in the paper by Sawicki & Mierczyński (2008). Fig. 3a shows a scheme of experimental set-up, and an example of experimental results is presented in Fig. 3b.

![Experimental set-up](a)

![Vertical displacements](b)

Fig3. Experimental set-up for determination of the viscosity of liquefied soil (a); vertical displacements of the cylinder sinking in liquefied soil (b)
6. SINKING OF STRUCTURES

Liquefaction of subsoil is the reason of such extreme phenomena as sinking of various structures, their uneven settlements or floatation of pipelines, see Sumer et al. (2007). A very simple model that enables the assessment of sinking of heavy objects in a liquefied subsoil was proposed by Sawicki & Mierczyński (2008). The equation of motion is derived from the equilibrium of vertical forces acting on the structure which include the own weight of the block Q, buoyancy W and the viscous damping force V. For a slow motion, the added mass may be neglected and this equation takes a simple form: Q = W + V, see Fig. 4a. The most difficult problem is how to determine the viscous damping force.

In fluid mechanics, there exist some classical solutions dealing with estimations of such forces acting on bodies falling down in the viscous fluid. The best known is the Stokes equation derived for a sphere, or the solution for a disk. Such approximations apply when the velocity of motion is small and the viscosity of fluid is large, as in the case of sinking in liquefied soil. In this case, the Reynolds number is very small and the general formula for the viscous damping force can be assumed as follows:

\[ V = \xi D \eta v, \]  

(5)

where \( \xi \) is a certain coefficient; D is a characteristic dimension of a sinking body as, for example, the diameter of a sphere or disk; \( v = dz/dt \) is the velocity. For the sphere, there is \( \xi = 3\pi \approx 9.43 \), and for the disk \( \xi = 8 \). We could not find in the literature values of \( \xi \) for other shapes of bodies, so they should be estimated. The most simple estimate is based on the assumption that V depends on the area of a base of a body considered, perpendicular to the direction of motion. For a low Reynolds number, the shape of a body should not significantly influence the value of \( \xi \). Therefore, it was decided to apply the disk approximation for different shapes, where D has a meaning of substitutional diameter. The equation of motion takes the following form:

\[ \frac{dz}{dt} + az = b, \]  

(6)

where \( a = \gamma_m A / \xi D \eta; b = Q / \xi D \eta \). A is the area of the base of the object; \( \gamma_m \) is the own weight of the solid-water mixture. The solution of this equation, with the zero initial condition is straightforward:

\[ z = \frac{b}{a} \left[ 1 - \exp(-at) \right]. \]  

(7)

Fig. 4b shows the curve (7), corresponding to the apartment building.
7. SUBMARINE LANDSLIDE

Liquefaction-induced submarine landslides can also be simulated using the model of viscous flow, which is defined by the Navier-Stokes equations and the continuity condition. For a slow fluid motion, these equations take the following form:

\[
\frac{\partial v_x}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial z^2} \right),
\]

\[
\frac{\partial v_z}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left( \frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial z^2} \right) - g,
\]

\[
\frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z} = 0,
\]

where \( v_x, v_z \) are the horizontal and vertical components of the velocity vector; \( p = \) pressure; \( g = \) gravity acceleration; \( \nu = \eta / \rho \) is the kinematic viscosity; \( \rho = \gamma_m / g \) is the density of liquefied soil.

Sawicki & Mierczyński (2008) have shown how the system of Eqs. (8-10) can be simplified and solved numerically for given boundary conditions. Fig. 5 shows a simulation of viscous flow of liquefied submarine slope.
8. LARGE DISPLACEMENTS OF QUAY-WALLS

Earthquake-induced displacements of heavy structures like, for example, quay-walls may be measured even in meters, see literature quoted in Sawicki et al. (2007). Review of existing approaches have shown that there is a lack of simple and convincing methods that would enable realistic simulations of the dynamics of such structures during earthquakes. Therefore, we have proposed a model in which a rigid block is subjected to both the horizontal and vertical ground accelerations. Simple equations of motion were derived and then solved numerically for given histories of ground acceleration. The model was validated in the laboratory. The tests were performed using a model block resting on a shaking table. The movements of a block and support were measured independently. Then, the movement of a block was predicted for given accelerations of the support, and predictions compared with measurements. Quite a good agreement was obtained which means that the model proposed leads to realistic results. Fig. 6c illustrates the movement of a typical quay-wall subjected to pseudo-stochastic horizontal and vertical ground accelerations (Figs. 6a and 6b). The solid line corresponds to horizontal displacements of the subsoil, whilst the broken line corresponds to the horizontal motion of the block. After some 9 seconds, the relative displacement of the block with respect to subsoil is about 0.5m in this special case. For details see Sawicki et al. (2007).
9. FINAL REMARKS

An outline of some results, obtained in the Institute of Hydro-Engineering, which deal with some aspects of coastal dynamics during earthquakes was presented. Details can be found in the literature quoted. It is hoped that this outline will show our possibilities and will be helpful for creation of joint research projects.

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REFERENCES


