Bulletin of Environment, Pharmacology and Life Sciences
Bull. Env. Pharmacol. Life Sci.[Spl. Issue 1] 2016: 44-49

Online ISSN 2277-1808
Journal's URL:http://www.bepls.com
CODEN: BEPLAD
Global Impact Factor 0.876
Universal Impact Factor 0.9804
http://doi-ds.org/doilink/05.2016-13212626/

OPEN ACCESS

Failure of Embankment dams founded on alluvium due to liquefaction under earthquake conditions using PLAXIS program

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ABSTRACT
Liquefaction is one of the most important and complicated issues in geotechnical earthquake engineering. This issue is very important in Iran due to locating in a high-risk seismic zone and constructing embankment dams. During this phenomenon, pore water pressure is increased, and becomes equivalent to total stress. Therefore, effective stress becomes zero and the soil shear strength will be equal to zero and becomes unstable. The present study aimed to assess failure of embankment dams due to liquefiable soil layers in their foundations using PLAXIS program. The main objective of this study was to determine the proper depth to liquefiable soil layers which are inevitable. Sampling these layers was not possible because of high costs.
Keywords: liquefaction, embankment dams, depth, standard penetration test.

Received 21.09.2016 Revised 14.10.2016 Accepted 01.11.2016

INTRODUCTION
Liquefaction is one of the most important geotechnical phenomena which destroys structures such as dams during earthquakes. This phenomenon usually occurs in loose saturated sandy soils. In this phenomenon, the interaction between solid and liquid phases of soil increases pore pressure due to the ground periodic motion which results in reduction of effective stresses in the soil and soil shear strength disappears. Dams built on saturated sediments such as sandy layers, are susceptible to liquefaction and failure during earthquakes.
Seismic safety evaluation of earth-fill structures such as embankment dams with liquefiable soil in their body or alluvial foundation is one of the most important issues in geotechnical engineering. Awareness of the severity of earthquake hazards has been increased because of the experiences of earthquakes occurred in the last 35 years. In the past, the most important concerns were about the high overburden pressure on foundations made of loose sands and silts and compressible layers, numerous subsidence events, pore water pressure and problems resulting from seepage and erosion. Recently, liquefaction issues have been added to these problems. Liquefaction may exacerbate effects of the earthquake dynamic force [1]. Liquefaction in dam foundation may lead to total destruction or create large and lasting deformations in the body. Paying attention to the depth of the liquefiable layer in the embankment dams foundations under seismic conditions is very important. This factor can affect the amount of damages to embankment dams. In the present study, a non-homogeneous embankment dam with clay core and alluvial foundation made of saturated silty sand was studied under seismic conditions conventional in Iran.

LITERATURE REVIEW
The term liquefaction was used by Hazen for Calaveras dam failure in California for the first time in soil mechanics. He explained the reason of liquefaction of the dam earthen walls as follows:
If the pore water pressure between soil grains is high enough to withstand the load, it may lead to separate soil grains by water, so that the soil condition becomes flowing sand condition. It means that by moving a part of material, an overload pressure is happened inside it, which results in moving another particle and gradually flowing like a liquid.
Liquefaction was the main reason of destructions in San Francisco during the 1989 Loma Prieta earthquake, in Kobe port during the 1995 Great Hanshin earthquake, as well as the 1964 Niigata and the

1964 Alaska earthquakes. Moreover, the severe destructions occurred in residential area and suburbs of Christchurch in New Zealand during the 2010 Mentor Barry earthquake and the more severe destructions in the 2011 New Zealand earthquake were all due to soil liquefaction.

Similar phenomenon to soil liquefaction

As noted, the term soil liquefaction is commonly used for introducing a number of similar phenomena. Because, these phenomena have similar effects and it is difficult to distinguish them from each another. These related phenomena are generally divided into the following two categories [2]:

Flow liquefaction

Flow liquefaction is a phenomenon in which static equilibrium of sedimentary soils with residual resistance is disturbed due to static or dynamic loads. Residual resistance is the resistance of liquefied soil. For example, the static load caused by a new building built on the slope can lead to additional force to the soil under the foundation. Earthquakes, explosions, and pile driving are examples of dynamic loads that can cause flow liquefaction. After the first liquefaction, soil becomes susceptible to flow liquefaction so that the soil has not sufficient resistance to withstand static stresses the same as before the turbulence. The fast and massive movement of the soil is of the features of this phenomenon. For instance, we can mention destruction of Kawaguchi building during the 1964 Niigata, Japan earthquake.

Further liquefaction

This phenomenon is caused by repetitive loading on sedimentary soils with static shear stresses less than the soil resistance. Deformations caused by periodic liquefaction are increasingly developed due to static and dynamic stresses during earthquake.

Lateral spreading of soil is one of the results of periodic liquefaction on flat and lower slopes areas along the seas and rivers. The 1976 Guatemala earthquake caused lateral spreading of soil along the Montague river. In flat areas, the high pore water pressure caused by liquefaction leads to fast water flow on the ground surface. This flow happens both during and after earthquakes. If the pore water flow is fast and raised enough, sand grains are moved toward cracks and sand boil phenomenon occurs. This phenomenon mostly occurs in areas affected by liquefaction.

Reducing liquefaction potential using soil modification

There are several methods that can be used to improve liquefiable soils below an area.

1- Excavation and replacing soils susceptible to liquefaction.
   a) Excavation and compaction engineering of the existing soil.
   b) Excavation and compaction engineering of soils modified by additives.
   c) Removal of existing soils and replacing them with non-liquefiable properly compacted soils.
2- Compression of residual soils.
   a) Compaction piles.
   b) Vibrating rods.
   c) Vibratory floating.
   d) Compaction grouting.
   e) Dynamic compression or impact compression.
3- Improvement of residual soils by changing them.
   a) Mixing residual soils with additives.
   b) Removing residual soils with geysers and replacing them with non-liquefiable soils.
4- Grouting or chemical stabilization.
   Grouting or chemical stabilization is the fourth category of soil modification techniques. These techniques improve shear strength of the soil by injecting particulate matters, resins or chemicals into the pores.

Situations in which liquefaction is not probable

1- Cohesive soils with more than 50% fine-grained materials containing a significant amount of clay.
2- Compact soils.
3- Soil mixtures of sand and cohesive fine materials with considerable amount of fine-grained and fine materials.
4- When the depth of the groundwater table exceeds 3 meters for moderate intensity earthquakes, 6 meters for high intensity earthquakes and 10 meters for severe earthquakes.
   In this case, liquefaction does not occur at the surface, but it may occur at the depth below the groundwater table. In such a situation, if deep foundations are used or shallow foundation is located at a considerable depth from the ground surface, liquefaction may damage the structure. In this case:
   - In shallow foundations, the groundwater table must be measured to the base of the foundation.

- In deep foundations with end resistance, the groundwater table must be measured to the top of the pile.

Situations in which liquefaction is probable

1- Loose and semi-dense sandy soils.
2- Mixture of gravel and sand, loose to semi-dense gravelly sands.
3- Loose to semi-dense silty sands.

Groundwater table must be less than 3 to 6 meters in the above situations.
If the soil and environmental conditions are in accordance with one of the above conditions, serious and detailed studies should be conducted to examine the possibility of preparations by an expert geotechnical engineer.

Evaluating the probability of liquefaction at embankment dam site

According to locating in a high-risk seismic zone and constructing embankment dams, evaluation and assessment of liquefaction which is one of the problems of the most earth-fill structures adjacent to water seems necessary in Iran. There are numerous methods to assess the probability of liquefaction including Cone Penetration Test (CPT), Standard Penetration Test (SPT), shear wave velocity measurement, and Becker Penetration Test [3].

Flow deformations caused by liquefaction

Flow liquefaction (resistance in stable conditions) and limited liquefaction should be separated in investigating earthquakes impacts on the alluvial foundations of dams. It is not possible to accurately estimate deformations created by liquefaction without accurate estimation of the residual resistance of the soil pore water overpressure at depth [4].

Soil residual resistance

In Duncan Dam, equation σ'_{vo} =0/21 S_{ur} was obtained between the residual resistance (S_{ur}) and limited effective stress (σ'_{vo}) to assess liquefaction in alluvial foundation using triaxial tests applied on frozen undisturbed samples. In the field method using SPT numbers, equation σ'_{vo} =0/10 S_{ur} was obtained. Residual resistance was applied as a function of limiting effective pressure in seismic evaluations of Sardis dam and several reservoir and tailings dams with σ'_{vo} = (0/06 -0/1) S_{ur}. The following empirical equation can be also used to estimate the residual resistance [5]:

S_{ur}/σ'_{vo} =0/06 + 0/025 ($(N_1)_{60}$ -6) $6 \leq (N_1)_{60} \leq 30$ (1)

The effect of limiting stress on the creation of the pore water overpressure

Based on the experimental results, the pore water overpressure created by cycle loading in the sample is reduced by increasing over consolidation ratio and the initial effective stress (in comparison with normally consolidated sample). By reducing pore water overpressure created by increasing depth in the alluvial foundations of dams, strain and deformation of liquefiable elements are significantly reduced [6]. Therefore, although the pore water overpressure is created due to increasing depth during the earthquake, but the resistance reduction is limited and liquefaction has less risk in the case of high effective tensions. However, based on centrifuge studies, the pore water overpressure less than 100 percent is limited to effective stresses larger than 3 atmospheres (300kPa) which is reduced for effective limiting stresses larger than this value. In fact, by increasing depth, density and resistance to liquefaction are increased. Moreover, liquefaction often occurs at depths less than the top 15 meters and saturated layer of sandy deposits and its effect is reduced at deeper levels.

METHODOLOGY

Estimation of soil resistance to liquefaction is the most important step in many geotechnical studies in earthquake-prone areas of the world. Approximation and calculation of two variables is necessary in order to assess soil resistance to liquefaction. These two variables are:

1- Seismic demand of soil layer (CSR).
2- Capacity of the soil to resist liquefaction (CRR).

CSR estimation method

Seed and Idris (1971) proposed the following equation to calculate CSR:

$$CSR = \left(\frac{\tau_{av}}{\sigma'_{v0}}\right) = 0.65\left(\frac{a_{max}}{g}\right) = \left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) r_d \qquad (2)$$

Where, a_{max} is the maximum horizontal acceleration caused by the earthquake, g is the gravitational acceleration, ‹σ_{v0} is the total overhead stress, σ'_{v0} is the overhead stress, and r_d is the stress reduction factor.

For common tasks and less sensitive projects, the following equations have been presented for calculating the average value of r_d (Liao and Whitman (1986):

(3) $z \leq 9.15m$ $r_d = 1 - 0.00765z$

(4) $$r_d = 1.174 - 0.0267z \quad for \quad 9.15m < z \leq 23m$$

CRR estimation methods

The best way to estimate CRR is testing undisturbed samples. Unfortunately, conditions governed on the studied soil cannot be created in the laboratory. Also obtaining undisturbed samples of granular soils is very difficult and costly. Soil disturbance leads to inaccurate results in the common sampling methods. Freezing is the best sampling method for these soils [7]. But the cost is very high and this method is applicable only for highly sensitive projects. For this reason, field methods of estimating soil resistance to liquefaction have been developed for insensitive tasks, and we will explain them in the next sections.

The most common way to estimate soil resistance to liquefaction is a simplified procedure proposed by Seed and Idris. They presented criteria for estimating soils liquefaction using SPT test results and the correlation between SPT test results and CSR parameter.

We can calculate CRR according to corrected SPT number and using the following equation (Rach (1998)):

$$CRR_{7.5} = \frac{1}{34 - N_m} + \frac{N_m}{135} + \frac{50}{(10N_m + 45)^2} - \frac{1}{200} \quad (5)$$

Where N_m is the resistance measured by SPT test based on the number of impacts.

Alavian dam

Alavian dam has been constructed over Sufi-Chai river in a 3.5 km-distance in the northwestern of Maragheh in East Azerbaijan province. Sufi-Chai river comes from Sahand mountains and flows into Urmia Lake after crossing the western of Maragheh and southern of Bonab. The aim of constructing Alavian dam was to collect and control Sufi-Chai flow for Maragheh city and military garrison drinking water supply, compensating a part of the shortage of irrigation and agricultural needs of Maragheh plain and surrounding gardens as well as hydroelectric power generation.

Alavian dam is an embankment dam with clay core and the height of 80 meters from the bedrock. The dam crest length is equal to 935 m and its width is equal to 10 meters. The total volume of the dam is equal to 4.8 million cubic meters. In order to improve the quality of bedrock in the foundation and flanks, watertight is constructed by drilling to a depth of 49 m in a main row and two auxiliary rows with lower depth. The overflow elevation is equal to 1568 m above sea level, the dam crest elevation is equal to 1572 m above sea level, and normal water table of the reservoir is equal to 1568 m above sea level. The volume at normal table is equal to 60 million square meters, the usable volume is equal to 57 million cubic meters and the adjusted water volume is about 123 million cubic meters per year.

Alavian dam foundation contains white, gray and pink tuffs with different physical - mechanical properties. Based on surveys conducted at the Alavian dam site, there are three major faults and some minor faults along, more or less, North – South direction which have created three distinct blocks.

Alavian dam spillway is lateral and designed and constructed with a length of 60 m and a maximum discharge of 1180 cubic meters per second on the dam's right abutment. Water overflows through a side channel with variable width of 8 m at the upstream and 20 m at the downstream, and a lateral slope of 10%. Shooting is designed and implemented from a part with rectangular cross-section, a length of 70m, a width of 30 m and the slope of 9.4% to the stilling basin with trapezoidal cross-section, a length of 40 m and the slope of 33%. Stilling basin is located at the downstream of the shooting with a length of 50 m and a width of 30 m.

In Alavian dam, the gallery is constructed with U-shaped cross-section and 2.9*2.4 m dimensions and a length of 970 m at the dam axis under the clay core foundation in order to perform the injection process, install piezometers, collect and redirect water leakage, menstrual visits and possible repairs during operation.

Deviation of the river flow during the construction period was obtained by two galleries with total length of 370 m (one with a U-shaped cross-section and dimensions of 3.5*4 m and the other one with a foursquare cross-section without corner and dimensions of 2.5*4.5 m) and a maximum design capacity of 150 cubic meters per second. After completion of the dam construction, galleries are used as deep discharge and irrigation and drinking water outlet.

An introduction to PLAXIS software

PLAXIS is a software packages used to analyze deformations and stability of earth-fill structures using finite element method. Geotechnical problems require more advanced models for modeling nonlinear behaviors and soils time function, because soils show different behaviors under different conditions such as loading and hydraulically conditions in the soil environment. For leakage flow calculations and hydraulic analysis, PLAXIS considers pore overpressures caused by loading in addition to calculating the fluid pressure in static mode on the phreatic line, for undrained soil. Then it adds the two pressures together and applies the result as the fluid pressure for calculation of effective stress.

$P_{active} = P_{steady} + P_{excess}$

So, steady pressures are calculated based on phreatic line or water flow lines calculations. In this software, these pressures are input data, while pore overpressures are the pore pressures created in the case of undrained materials with low permeability factors, such as clays, under loading.
The software allows to calculate the water flow inside the soil and it calculates and plots the phreatic line based on the mentioned basic concepts, if there is a pressure difference between two environments considering all boundary conditions for inlet and outlet water flow between two environments which can be presented in their interface. Then the flow lines and the potential lines are calculated and plotted based on the phreatic line.

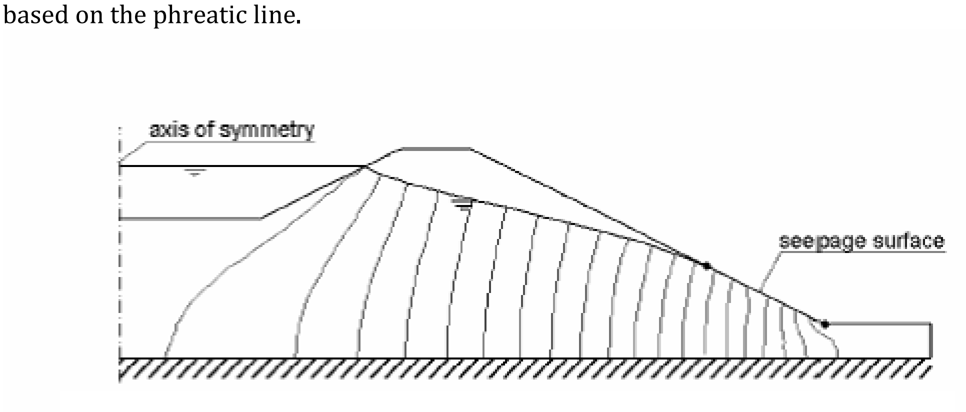

Figure 1.1 Flow through an embankment with indication of a seepage surface

Software uses the critical state model and modified Cam-Clay model for modeling the mechanical behavior of materials. Therefore, the yield surface in this software represents an ellipse in the P'-q space shown in Figure 1.2.

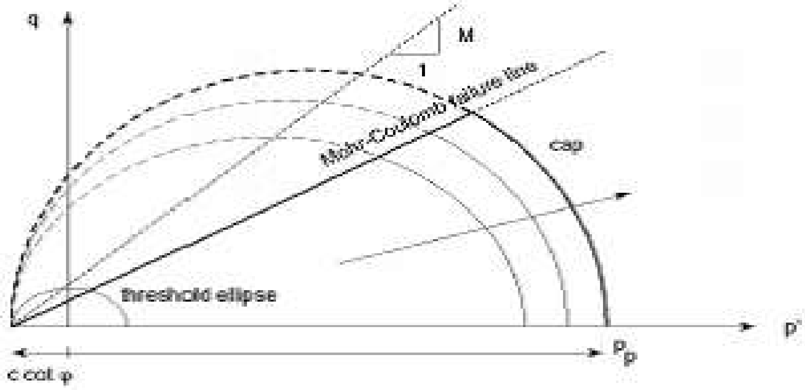

Figure 1.2 Yield surface of thr Sofgt-Soil model in p-q-plane

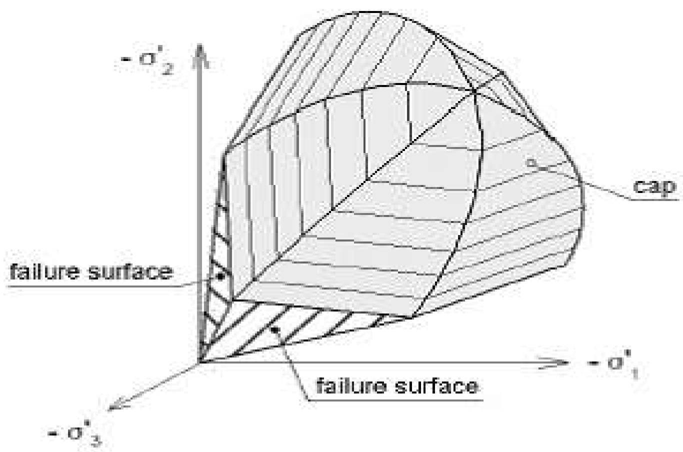

Figure 1.3 Representation of total yield contour of the Soft-Soil model in principal stress space

CONCLUSIONS

Liquefaction is a phenomenon caused by a sudden increase in pore water pressure, reduction of effective stress between soil particles, and consequently a sharp reduction in shear strength which could eventually lead to local or complete destruction of structures built on soils. The reasons for large displacement of embankment dams founded on alluvium include low shear strength of alluvial foundation, liquefaction at upstream and downstream, and further increase in entering bedrock into alluvial foundations in comparison with stone foundations. According to the results, in order to maintain the stability of the dam during an earthquake, removing alluvial foundation on the basis of common methods is necessary unless a comprehensive numerical and physical evaluation has led to effective techniques for improving the stability of alluvial foundation in maintaining dam stability.

Alluvial foundations usually have more problems than the stone foundations. Because they have usually less resistance, higher deformation and higher permeability then stone foundations. These foundations have usually high erodibility. Furthermore, in special conditions they may also be susceptible to liquefaction.

Previous studies show that by increasing depth of alluvial foundation, liquefaction, subsidence and other risks are reduced. The important problem of existing alluvial layers in embankment foundations is the embankment dam subsidence before liquefaction under an earthquake. These layers, due to the weakness in the structure, subside under low pressures and lead to destroy the dam or permanent deformations in its body. Therefore, existence of alluvial foundation at shallow depth, about 3 and 7 m before being important in terms of liquefaction, must be studied in terms of subsidence. In the present study, in the case of Alavian dam, if there is alluvial layer in its foundation, there is a serious risk of subsidence to depth of 12 m. The most appropriate depth for locating alluvial layer is down to 12 m to have no danger to the dam.

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