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LIQUEFACTION POSSIBILITYOF SOIL LAYERS DURING EARTHQUAKE IN HANOI

Gospodarikov Alexandr [1] and Thanh Nguyen Chi [1, 2]*

[1]Faculty of Construction, Saint Petersburg Mining University, Russia; [2]Hanoi University Mining and Geology, Vietnam

*Corresponding Author, Received: 13 June 2017, Revised: 28 July 2017, Accepted: 10 Aug. 2017

ABSTRACT: Earthquakes are one of the most unpredictable natural phenomena that can damage buildings on the surface as well as underground structures. It is therefore necessary to have an effective and accurate assessment of the impact of earthquakes on existing structures. Hanoi is the capitol and second largest city in Vietnam and contains many historical and important buildings. Previous studies suggest that Hanoi may be affected by earthquakes occurring along the Lai Chau - Dien Bien - Son La and Red River faults. Parameters of earthquakes that could occur in Hanoi are studied using common methods (e.g. Campbell and Seed, etc.). Based on the data collected from the studies about some characteristics of the strongest earthquakes that can occur in the Hanoi area, this study presents an estimate of the possibility of liquefaction of soil layers in Hanoi during an earthquake in combination with experimental results obtained under relevant geological and hydrogeological conditions.

Keywords: Earthquake, Magnitude, Liquefaction, Soil.

1. INTRODUCTION

Hanoi is the capital of Vietnam with a population of approximately eight million. The city continues to rapidly develop with many buildings and important structures. Hanoi is located in an area affected by the Lai Chau - Dien Bien - Son La faults [1]. The possibility of Hanoi being affected by earthquakes is therefore significant. Additionally, Hanoi is in the plain of the Red River and is affected by high groundwater levels. Due to the city's risk of being affected by both earthquakes and saturated water, the soils in the Hanoi area may change to the liquid state. This phenomenon can significantly affect the stability and sustainability of structures in Hanoi, especially underground structures such as the Hanoi metro tunnel system. There are currently no results in the literature regarding the possibility of soil liquefaction in the centre of Hanoi under the impact of an earthquake. The current study aims to estimate the possibility of soil layer liquefaction due to an earthquake in the context of the relevant earthquake and hydrogeological and geotechnical conditions in Hanoi.

2. CHARACTERISTICS AND PARAMETERS OF EARTHQUAKES IN HANOI

Vietnam is located in the centre of Southeast Asia and may be strongly affected by relative movements between the Mediterranean and Himalaya belts. The tectonic conditions in this region are the cause of moderate seismic activity and complicated geological structures along many zones in Vietnam, such as the Lai Chau - Dien Bien (LC–DB) and Red (Hong) River faults (Fig.1). In the 20th century, there were two earthquakes with magnitudes M_W 6.7 and M_W 6.8 on the Richter scale [1], and more than 20 earthquakes of M_W 5.0–5.6. These earthquakes caused great damage to houses, infrastructure and also a loss of human life. With a short distance to the large regional faults (20–50 km), substantial effects of the earthquakes can occur in Hanoi. Therefore, it is necessary to have a thorough understanding of the possible impacts of earthquakes in Hanoi in order to implement preventive methods and mitigate the negative consequences that could occur.

Based on the data collected from the above studies, some characteristics of the strongest earthquakes that can occur in the Hanoi area are:

- Earthquake with a maximum M_W of 6.5;
- Distance from the epicentre of the earthquake to Hanoi is 20 to 50 km.

The equations and graphs of [2] are used to find the maximum ground acceleration that occurs in Hanoi:

$$A=0.0159e^{0.868M_W}[R + 0.0606e^{0.7M_W}]^{-1.09} \quad (1)$$

Where A is the peak ground acceleration, and R is the distance to the fault in km. According to [2]:

$$\log(A)= -1.02+0.249M_W - \log(r) - 0.00255r \quad (2)$$

Where $r = (R^2+7.3^2)^{1/2}$.

Based on Eqs. (1) and (2), Fig.2 presents the relationship between *R* and *A* in the case of an M_W 6.5 earthquake. It can be seen that an *A* value of 0.2 can be predicted for this scenario in Hanoi.

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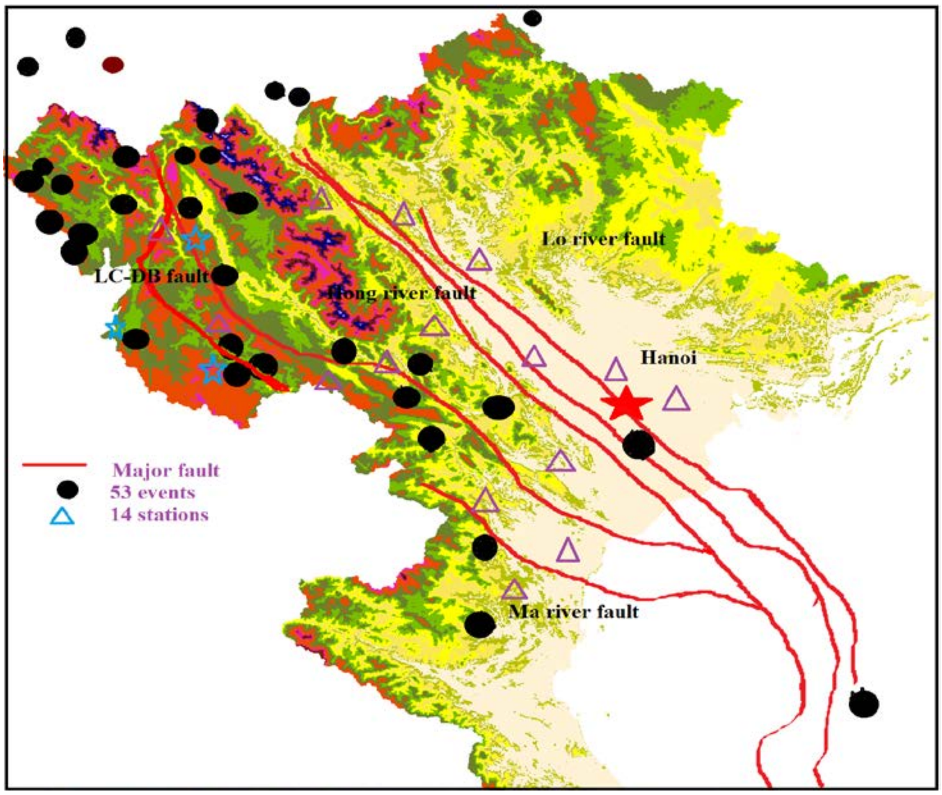

Fig.1 Map of the major fault systems, 53 events used in this study and the 14 portable broadband stations in northern Vietnam. The two strongest recorded earthquakes (in 1935 and 1983), as well as the 1983 Dien Bien earthquake, are indicated by the three open stars [1]

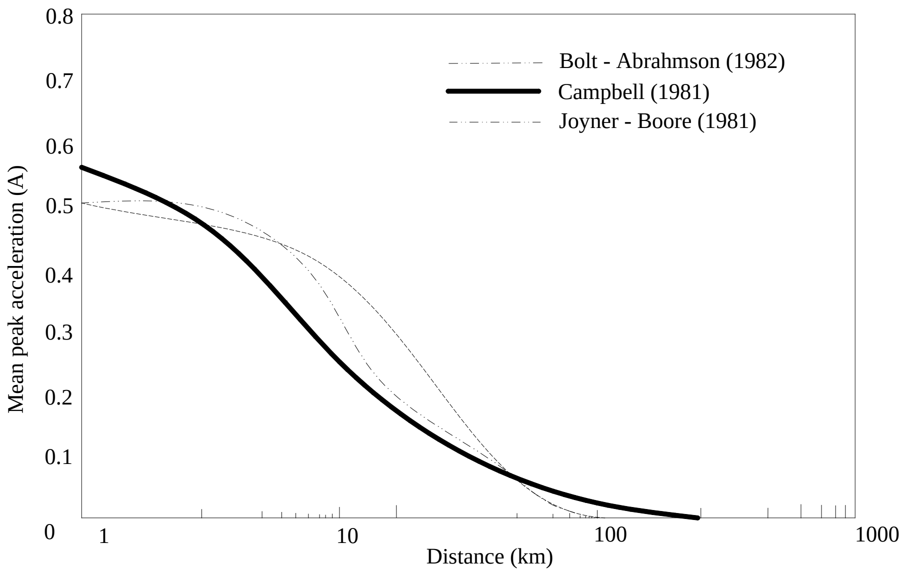

Fig.2 Comparison of recent correlations between the horizontal peak ground acceleration and distance to the earthquake epicentre (modified from [2])

3. POSSIBLE LIQUEFACTION OF SOIL LAYERS IN HANOI UNDER THE IMPACT OF EARTHQUAKES

Under the impact of an earthquake, soils in the affected area may be changed to the liquid state depending on a variety of factors including the earthquake magnitude, distance from the epicentre, soil characteristics, saturation conditions of the affected area, etc. Soils with low physical characteristics, such as alluvial soils, will be the most affected.

Soil liquefaction is a process that occurs over a very short period of time (several seconds or tens of seconds) during strong ground shaking when the soil transforms from its normal solid state into a heavy liquid mass. As a consequence, the soil essentially loses its strength and bearing capacity (i.e. capacity to support the loads of heavy structures), which thus causing sinking of heavy structures into the ground. Conversely, light and buoyant structures with a smaller mass density than the liquefied soil mass will be uplifted and float above the surface. This is a significant problem for underground infrastructure in the affected areas.

3.1 Hydrogeological and engineering geological conditions in Hanoi

The groundwater level in Hanoi is quite high, which can therefore cause liquefaction phenomena in the soils. According to surveying experiments in the central area of Hanoi, the hydrogeological and geological conditions are as follows: the ground water level is three metres below the surface; there are usually six layers of soils distributed from the ground surface to the bedrock at a depth of 48 m.

Table 1 Parameters of soils in Hanoi centre [3,4]

Number of soillayers	Elastic module, E, MPa	Poisson's ratio, μ	Thickness of layer (h), m	Density of the soil, ρ, g/cm^3	Ground water level, m
1	9.25	0.41	4.6	1.75	3.0
2	7.68	0.38	1.1	1.76	
3	15.3	0.35	11.8	1.81	
4	35.02	0.33	12.5	1.78	
5	53.9	0.32	11.0	1.83	
6	65	0.3	7.0	1.86	

3.2 Liquid limit of soil in central Hanoi during an earthquake

At present, there are many methods to estimate the liquid limit of soil. In this study, we use data from the Standard Penetration Test (SPT) to evaluate the liquid limit of soil during an earthquake of the greatest magnitude that that can could occur in Hanoi.

The primary method for analysing liquefaction hazards employed in the United States and many other countries is the simplified procedure developed by [5]. In order to evaluate the liquefaction hazard at a given site, the simplified procedure requires several correction factors to account for conditions that differ from those directly obtained in the technique derivation. The magnitude scaling factor (MSF) corrects the analysis for earthquakes with M_W other than 7.5, which is the standard used at the time of derivation.

Seed's method is based on the shear stress of a soil layer that is subjected to an earthquake. The maximum cyclic shear stress of clean sand stratum at depth Z is estimated by the equation [5, 6]:

$$\tau_{\max}=\frac{a_{\max}}{g}\left(\gamma_t Z\right)r_d \tag{3}$$

Where $\tau_{\max}$ is the maximum shear stress, $a_{\max}$ is the maximum horizontal acceleration at the ground surface, g is the acceleration of gravity, γ_t is the total unit weight of the soil and r_d is the stress reduction coefficient, which may be approximated [7] as:

$r_d = 1.0–0.00765Z$ when $Z < 9.15$ m;
$r_d = 1.174–0.0267Z$ when $9.15 \leq Z \leq 23$ m;
$r_d = 0.744–0.008Z$ when $23 < Z \leq 30$ m;
$r_d = 0.5$ when $Z > 30$ m.

The field deposit is thought to undergo an average stress τ_{avg}, which is 0.65 of $\tau_{\max}$. The τ_{avg} value is then normalised by the vertical effective stress to give the cyclic stress ratio:

$$\frac{\tau_{avg}}{\overline{\sigma}_v}=0.65\frac{a_{\max}}{g}\left(\frac{\sigma_v}{\overline{\sigma}_v}\right)r_d \tag{4}$$

where σ_v is total vertical stress and $\overline{\sigma_v} = (\sigma_v - u)$ is total vertical effective stress, where u is pore water pressure.

As can be seen in Fig. 3, there is an obvious dividing line between the domain of where liquefaction was present and where it was not for M_W 7.5 earthquakes. An investigator merely corrects the field blow counts to $(N_1)_{60}$, calculates the cyclic stress ratio for the design earthquake and checks Fig. 3 to see if the sand is likely to liquefy. Correction factors were given to extend this method to different magnitude temblors and for silty sands. Based on the idea that the functional difference between magnitudes is only the number of stress cycles, a table of factors are cyclic stress ratio for quakes other than $M_W = 7.5$ [5].

The cyclic stress ratio serves as the link between the peak acceleration of an earthquake and the dynamic shear stress applied to the soil at depth. As stated previously, the SPT is the most commonly run test for field investigations, and there exists a very large number of N-values reported from many sites around the world. Seed and colleagues assembled a database of more than one hundred records of SPT tests taken at sites that liquefied, as well as sites that could have liquefied and did not. Most of these records were for sites affected by earthquakes with M_w of 7.5. Blow counts were corrected for all known variables to yield $(N_1)_{60}$ so that, in theory, all the SPT values were comparable. A plot was then made (Fig.4) of the cyclic stress ratio vs. $(N_1)_{60}$, and a boundary drawn between the values for liquefied and non-liquefied sites.

Re-evaluation of field datasets and laboratory tests on frozen samples led to a revised magnitude scaling factor [4,8]:

Table 2 Comparison of the effect of event magnitude [5]

	Earthquake Magnitude Scaling Factors		
Magnitude	(Seed et al.,1983)	(Ambraseys, 1985)	(Loertscher&Youd, 1994)
8-1/2	0.89	0.44	0.62
7-1/2	1.00	1.00	1.00
6-1/2	1.19	1.69	1.88
5-1/2	1.43	2.86	4.46

$$MSF=31.9(M_W)^{-1.72} \quad (5)$$

However, by means of experimentation and data synthesis, scientists have found that there are quite a number of factors that influence soil liquefaction during an earthquake. For example, fine dust particles in the soil (FC) are one of the factors that greatly influence the soil's ability to liquefy. Therefore, when calculating the capacity and limitation of soil liquefaction during earthquakes, the effect of this factor should also be taken into account.

Cyclic stress-based analysis consists of the following steps [9, 10, 11]:
Step 1–Discretise boring log into a series of soil layers;
Step 2–Compute the vertical total stress (σ_{vo}) and vertical effective stresses (σ'_{vo}) for each soil layer;
Step 3–Determine M_W and a_{max} for the site;
Step 4–Determine r_d ;
Step 5 – Compute the cyclic stress ratio (CSR)

$$CSR = \frac{\tau_{avg}}{\sigma'_{vo}} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d \quad ; \quad (6)$$

Step 6–Compute $(N_1)_{60}$, the SPT blow count normalised to an overburden pressure of 100 kPa (1ton/ft^2), and hammer energy ratio or hammer efficiency of 60%;
Step 7–Adjust $(N_1)_{60}$ to account for fines content (FC) by calculating the equivalent clean sand value, $(N_1)_{60CS}$, such that the fines content correction can be estimated by [7, 9, 12,]:

$$(N_1)_{60CS}=\alpha+\beta(N_1)_{60} \quad (7)$$

$$\beta = \left[0.99+\left(FC^{1.5}/1000\right)\right] \quad (8)$$

$$\alpha = \left[1.76 - \left(190/FC^{1.5}\right)\right] \quad (9)$$

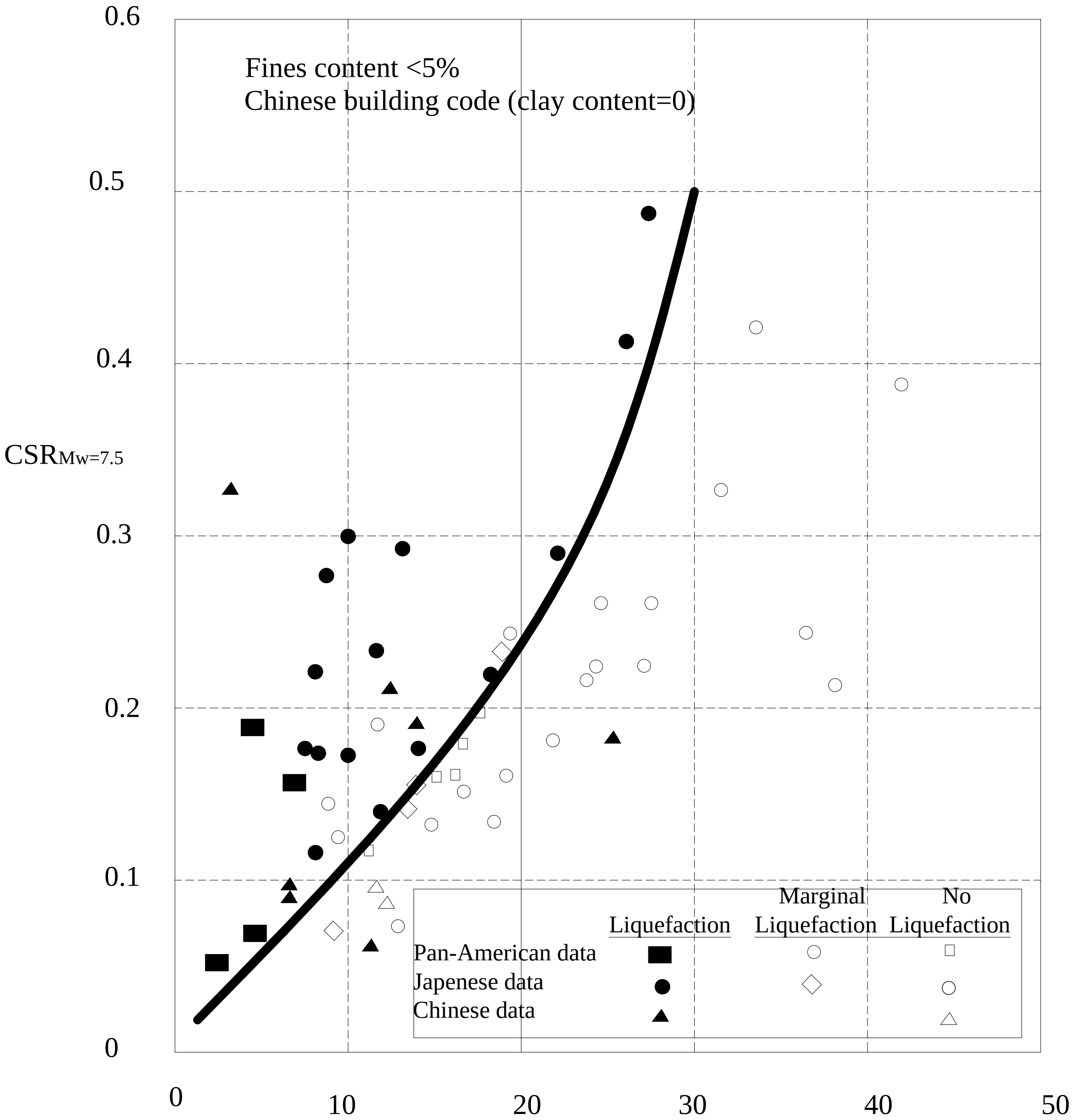

Fig.3 Relationship between cyclic stress ratios causing liquefaction and $(N_1)_{60}$ values for clean sands in magnitude 7.5 earthquakes [5,13]

Where *FC* is fines content in soil (%), $(N_1)_{60}$ is the equivalent clean sand SPT blow count and $(N_1)_{60CS}$ is the stress normalised SPT blow count correction for energy efficiency and fines content.
Step 8 – Calculate the cyclic resistance ratio ($CRR_{7.5}$) for an M_W 7.5 earthquake;
Step 9 – Calculate the MSF;
Step10–Adjust the cyclic resistance ratio for the actual earthquake magnitude (CRR_M);
Step 11 – Calculate the factor of safety (*FS*) against liquefaction.

When $FS \leq 1$, the investigated soil is likely to be liquefied. If $FS > 1$, the soil will not be able to liquefy. We apply these calculations to determine the potential for liquefaction of soil layers in central Hanoi during an M_W 6.5 earthquake. The results are as listed in Table 3.

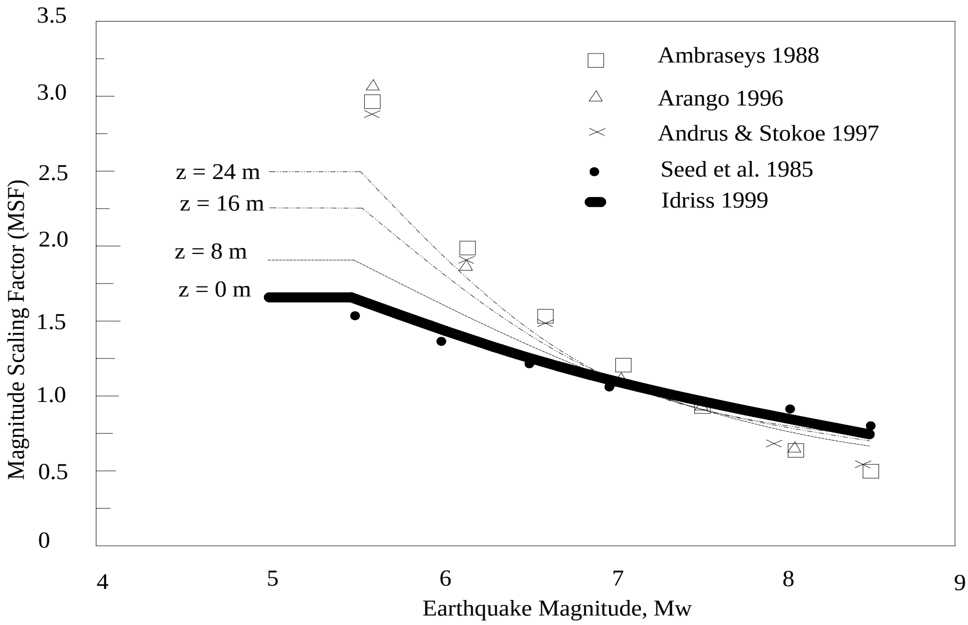

Fig.4 Effect of revised stress reduction coefficients on magnitude scaling factors [8, 10]

Table 3 Results of calculations to determine the potential for liquefaction of soil layers in central Hanoi during the largest possible earthquake

Number of layers soil	1	2	3	4	5	6
Depth, (h), m	4.6	5.7	17.5	30	41	48
Measured SPT blow count, N	4	8	13	20	28	31
Corrected SPT blow count, $(N_1)_{60}$	4.62	8.70	9.31	11.37	13.73	14.07
Shear stress reduction coefficient, r_d, m	0.96	0.96	0.71	0.5	0.5	0.5
Fines content *FC*, %	43	39	35	30	27	18
SPT blow count correction for energy efficiency and fines content, $(N_1)_{60CS}$	11.12	15.86	16.12	17.84	20.00	18.24
Cyclic stress ratio, CSR	0.16	0.17	0.17	0.13	0.13	0.13
Cyclic resistance ratio for magnitude 7.5 earthquake, $CRR_{7.5}$	0.1	0.6	0.18	0.21	0.22	0.21
Factor of safety (*FS*)	0.82	1.20	1.34	2.03	2.10	1.99

It can be seen from the results listed in Table 3 that, under the influence of an M_W 6.5 earthquake with $\boldsymbol{a}_{max}$ = 0.2$\boldsymbol{g}$, the top layer soil in central Hanoi will be liquefied (*FS* = 0.82 <1). Other layers of soil are not liquefied under the influence of the earthquake.

Triaxial compression experiments were carried out in the laboratory using soil samples collected from a 4.5-m deep drill hole fromcentral Hanoi. The samples were tested using the following experimental parameters: σ_1= 100 kPa (major principal stress); σ_3= 80 kPa (minor principal stress, cell pressure) and kept constant during the test; σ_0= 16 kPa (pore water pressure), soil compaction of sample, D_r= 0.53 and frequency f=2 Hz.

Fig.5 Components of the DS Triaxial Automated System (TAS) - Tritech 100 [4]

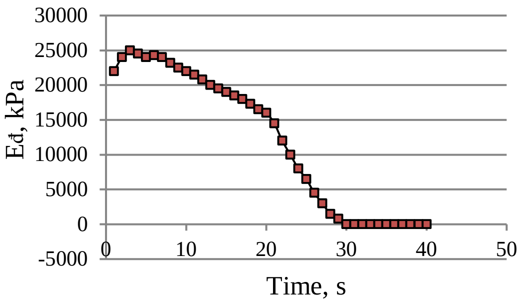

Fig.6 Change of deformation modulus of soil E_d according to loading cycle in triaxial compression test

The results of the experiments are presented in Fig.6. Under the influence of dynamic force in the triaxial compression test, when the soil is liquefied, the deformation modulus of the soil changes very rapidly and decreases to zero at time ***t***=30 s (Fig.6). Fig.7 shows the change of deformation in the soil sample according to the dynamic loading cycle. The soil is considered to be liquefied when deformation reaches a value of 5% corresponding to the testing time ***t*** = 29 s. From the results obtained in the triaxial compression test of soil samples described above, it can be seen that the soil in the first layer at the central area of Hanoi might be liquefied during an M_W 6.5 earthquake with $a_{max} = 0.2g$.

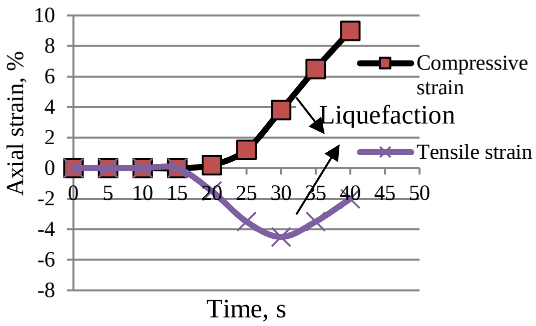

Fig.7 Change in deformation characteristics for soil samples as a function of the loading cyclein the triaxial compression tests

4. DISCUSSION AND CONCLUSION

Earthquakes are one of the most unpredictable natural phenomena and calculation of their effects is challenging. Different phenomena occur depending on the earthquake magnitude, distance from the epicentre to the affected area and the geological and hydrogeological conditions. One of the greatest effects of earthquakes is the liquefaction of soils in the affected area. In this study, the characteristics of an earthquake of the greatest possible magnitude in Hanoi, Vietnam have been depicted. Experiments on soils obtained from the central part of Hanoi were performed. Information regarding the geological and hydrogeological conditions in the area were collected and applied the theories to calculate the probability of liquefaction of soil layers in an M_W 6.5 earthquake, the strongest that can occur in Hanoi.

As Hanoi may be influenced by an M_W 6.5 earthquake at a distance from the epicentre of about 20 to 50 km, the peak acceleration of a_{max} = 0.2g was chosen. This value is different from that indicated in literature in which the value for M_w 5.5 and a_{max}= 0.1067g have been adopted. Under the latter condition, soil liquefaction will not occur. However, for an earthquake with larger M_W and a_{max} values of 6.5 and 0.2g, respectively, as proposed in this study, the top 5-m layer of soil in central Hanoi can be liquefied.

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6. AUTHOR CONTRIBUTIONS

Thanh Nguyen Chi compiledrelevant materials, performed experiments, analysed and interpreted data and drafted the manuscript as part of his PhD research under the supervision of Gospodarikov Alexandr, who revised the manuscript.

7. ETHICS

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues are involved. This article is original work and not under consideration for publication in any other journal. There are no conflicts of interest with this paper.

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