Recent Advances on Study of Liquefaction and Time to Failure of Sandy Subsoil

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ABSTRACT

The unacceptable nonlinear force on subsoil results in unallowable settlement, deformation and failure of soil foundation. The simulation of dynamic force propagation in saturated sand has been done by several researchers. The dynamic force induces pore water pressure and causes dynamic liquefaction in sandy subsoil. The characteristics of dynamic force along with the mechanical properties of soil are responsible for magnitude of dynamic liquefaction and time to failure of soil. In this paper, the effect of dynamic force propagation and dynamic pore water pressure on liquefied sand in associate to soil mechanical properties has been evaluated. To mitigate differential settlement of footing, a simple sandy semi-confined column has been proposed. The outcome of study has been revealed near realistic behavior of liquefaction and time to failure of footing.

KEYWORDS: Nonlinear force, pore water pressure, dynamic liquefaction, sandy column, liquefaction resistance

INTRODUCTION

The pore water pressure functions in sand helps to accurate predict liquefaction damage. The pore water pressure involves generation, distribution and dissipation. There are several factors govern liquefaction magnitude.

The liquefaction has been reported in several past earthquakes especially during Alaskan Earthquake (1964) and Niigata Earthquake (1964), it induces instability of subsoil and damage of infrastructures [1-2]. The realistic modelling of saturated sandy subsoil affected by dynamic force was not easy task due to multiscale, multiphysics computational framework requirement [3]. And the bearing capacity failure, permanent settlement with a slight residual tilt could be observed in layer which was under liquefaction [4], sometimes the damage on structure were not sever but it is decreased structures factor of safety. It was unknown about subsoil liquefaction resistance, liquefaction time, depth of subsoil induced liquefaction and accurate effect of liquefied layer on other parts of subsoil. As it is well known that the soil mechanical properties is associated to liquefaction magnitude.

The water seismic index (WSI) is a method to identify soil hydrological condition. It recognizes as a method to predict saturated and unsaturated soil [5]. And for the modelling and simulation earthquake induced liquefaction in loose and dense saturated subsoil the details of wave propagation in seismic response of saturated porous media numerically have been discussed [6]. There is a laboratory experimental modelling on isotropically consolidated saturated sand for simulating seismic response analysis through measuring shear wave velocity during cyclic liquefaction and analysis shear wave velocity effect on strain shear modulus during an earthquake [7]. In the saturated sand requires to analysis and understand of liquefaction resistance. It has been mentioned that the mechanical property of granular material has direct correlation with its fabric and it could be used for measuring stress-strain relationship and shear strength of soil [8]. And from other hand the gravelly soil is recognized to have no liquefaction but after 1999 Chi-Chi Taiwan earthquake and 1988 Armenia earthquake warranted the potential liquefaction of gravelly soil [9]. The existing problem was other investigation and alternative approach like work on support vector machine (SVM) to predict liquefaction of soil using shear wave velocity (Vs). This method has been developed by Vapnik, and the philosophy was based on statistical learning method [10]. And later others models have been developed using SVM through consideration of effective vertical stress, soil type, shear wave velocity, peak horizontal acceleration and earthquake magnitude [11]. To continue investigation on liquefaction resistance the database collected from other scientific [12], have been used for develop model for predict liquefaction resistance based on SVM model [10]. The earthquake nature play main role in liquefaction resistance. The different earthquake records have been studied for proposed a simple method to assess the liquefaction potential of a soil deposit [13]. The quantitative and qualitative seismic record is criteria for detecting site liquefaction vulnerability. However, the liquefaction prediction is depending on quantity of seismic record on liquefied soil. And the wave seismic transfer in the liquefiable and un-liquefiable is helped for prediction soil liquefaction resistance [14]. The multi-artificial neural network model for wave induced liquefaction has been shown the maximum liquefaction potential [15]. The result presented previous researcher could be used for further soil liquefaction resistance [16]. Although the investigation incorporating a wave model and soil model for soil liquefaction potential using non-breaking and breaking wave for modelling [17-18] and also wave induced liquefaction used for simulation of earthquake induced liquefaction [19]. To mitigate differential settlement of light structure footing, to improve time to failure of light structure footing, and to use advantage of liquefaction function for improve structure stability, to find appropriate place sandy column, the sand dynamic mechanical properties have been evaluated.

SITE GEOLOGICAL CHARACTERISTICS

The excess pore water pressure generally has been observed in fully saturated loose to medium dense sands subjected to the static or dynamic forces and resulted in shear stress higher than shear strength and implied zero effective stress [20]. During an earthquake this phenomenon periodically is repeated and the dynamic liquefaction will be produced and subsequently bring more deformation and instability to the subsoil. The soil liquefaction resistance has strong influence on dynamic liquefaction magnitude.

There is a research on Vietnam sand liquefaction resistance using shaking tests, the liquefaction possibility, settlement, bulk density, and shaking duration, dynamic force frequency, acceleration and dynamic force direction have been indicated in the Table 1. The one direction dynamic force reduced sand liquefaction resistance more compare to the multi-direction dynamic force [21]. The one direction dynamic force resultant has more ability in collapsing soil liquefaction resistance. The multi-direction dynamic force characteristic is improved soil liquefaction resistance. The logic behind is multi-direction dynamic force not allowed the granular particle be rearranged equal to sand subject to the one direction dynamic force and subsequently liquefaction magnitude reduced. The force in test E02 has same characteristics of test E01 and only direction is changed, in this case liquefaction was due to changing dynamic force direction. In the practical may be earthquake epicentre govern liquefaction magnitude when the site geological characteristics is constant. The second liquefaction case is test E08 the frequency is governing the liquefaction resistance.

It has also been observed increased frequency cased liquefaction [22]. And also may be wave time travel and angle of wave propagation in a soil can control sand liquefaction resistance. Reducing seismic settlement is a way of increasing soil liquefaction resistance. In initial of shaking the loose saturated sand faced settlement and in next coming shaking, the subsoil shows liquefaction resistance due to improved density. The occurrence of liquefaction is along with the settlement the good thing is the site faced previous earthquake in the future should show more liquefaction resistance due to liquefaction-settlement-density phenomenon, but it not mean no more liquefaction will be there.

The precise depth of liquefaction could be estimate using recorded excess pore water pressure and accelerations in different level of subsoil is subjected to the shaking [23]. The dynamic force direction also play main role in prediction sand liquefaction resistance. It is too important in earthquake geotechnical engineering to estimate liquefaction zone of subsoil for understanding structure safety and stability.

Table 1: Test sequence in shaking table tests series E, April 2004 [21]

	X (N-S)		Y (E-W)					
Shaking No	Frequency (Hz)	Acceleration (g)	Frequency (Hz)	Acceleration (g)	Duration (S)	Liquefaction (?)	Settlement (mm)	Bulk density (kg/m^3)
E01	2	0.03	-	-	10	Yes	14.7	1416
E02	-	-	2	0.03	10	No	0.5	1417
E03	2	0.03	2	0.03	10	No	0.7	1417
E04	2	0.03	2	0.03	10	No	0.6	1418
E05	-	-	2	0.05	5	No	0.7	1419
E05a	-	-	2	0.05	5	No	0.1	1419
E05b	-	-	2	0.05	5	No	0.4	1419
E06	-	-	2	0.05	10	No	0.3	1420
E07	-	-	2	0.05	20	No	0.4	1420
E08	-	-	4	0.05	10	Yes	9.1	1430
E09	-	-	4	0.05	5	No	2.4	1432
E10	-	-	1	0.05	10	No	0.1	1432
E11	2	0.05	2	0.05	5	No	0.1	1432
E11a	2	0.05	2	0.05	5	No	0.4	1433
E11b	2	0.05	2	0.05	5	No	1.3	1434
E12	2	0.05	2	0.05	10	No	0.4	1435
E13	2	0.05	2	0.05	20	No	1.5	1436

SEISMIC WAVE PROPAGATION AND LIQUEFACTION

Water seismic index (WSI) method has been used for identifying and exploration underground hydrological reservoir [5]. The method can be used for soil resistivity measurement, prediction of liquefaction and simulation of volumetric strain of granular soil. For estimation of liquefaction depth, the frequency, direction and magnitude of seismic wave propagation is more important.

The 3D finite element framework explained pore water pressure produced dynamic liquefaction during an earthquake [6]. There are many numerical simulation models with different level of accuracy have been introduced for dynamic pore water pressure evaluation [24-26]. Seismic wave propagation and pore water pressure relationship could be indirectly evaluated for liquefaction simulation.

It has been shown that the sand morphology is important in sand reliquefaction phenomenon and could improve resistance liquefaction [27]. And the grain characteristic such as gradation, particle shape, and uniformity significantly influences excess pore water pressure generation [28]. The sand particle morphology governs compaction level. And indirectly could be understand that the dynamic wave propagation of shaking table test was controlled by particle morphology. For numerically simulation of seismic wave propagation for liquefaction or re-liquefaction prediction the granular of site play significant role.

It was believed that the no liquefaction for gravelly soil. However, liquefaction cases were observed in central Taiwan in the 1999 Chi-Chi Taiwan earthquake and in the 1988 America earthquake. In an investigation has been finding that the large hammer penetration test (LPT) and shear wave velocity methods are acceptable for liquefaction resistance assessment of gravely soil [9]. The shear wave velocity is directly related to shear modulus at a small strain level and can be established without boring and penetration and it is applicable for measuring liquefaction resistance of gravely soil [29]. It has been realized that the most of failure during an earthquake is occurred due to shearing forces [30]. The liquefaction resistance, shear forcing and seismic wave propagation are three main factors governing soil seismic mechanical properties and from other hand the soil mechanical properties controls seismic wave propagation direction. The seismic wave propagation direction can governs the material vibration magnitude.

VOLUMETRIC STRAIN AND SEISMIC WAVE

The modifying cohesion less granular material for any reason is resulted in changing shear stress-strain behaviour and shear strength and subsequently leads to the changing liquefaction resistibility. If changing granular fabric due to wave propagation be feasible then it is possibility for furcating accurate liquefaction resistance.

The shear wave velocity helps prediction of liquefaction potential of soil [11], and this method has cost effective advantage compare to SPT and CPT methods [31]. The summery of a research work indicated that when the shear modulus of water-saturated loose soil increased, porosity decreased logarithmically. If shear modulus increases in dense or solid saturated soils, porosity decreases linearly. The pore water pressure (u), $u = kw/[\Delta Vw/\phi V]$ is depend on incompressibility of water (kw) and volumetric deformations $[\Delta Vw/\phi V]$, this concept [32], helps in prediction of soil liquefaction resistance and allowable volumetric deformation of subsoil. It is a feasible method for accurate designing vertical drainage for dissipation of excess pore water pressure before failure of soil liquefaction resistance. The good discussions on the vertical drains have been presented by various researchers [33-36]. There are several investigations on frozen soil behaviour [37-38]. The latest investigation was reported that the volume of frozen soils subjected to the shear is changed with temperature, confining pressure and soil type. This volumetric deformation is nonlinearly with axial deformation, changed cross-section, stress–strain and compressive strength [39]. The wave propagation in frozen soil will be entirely different compare to soil is under ordinary temperature.

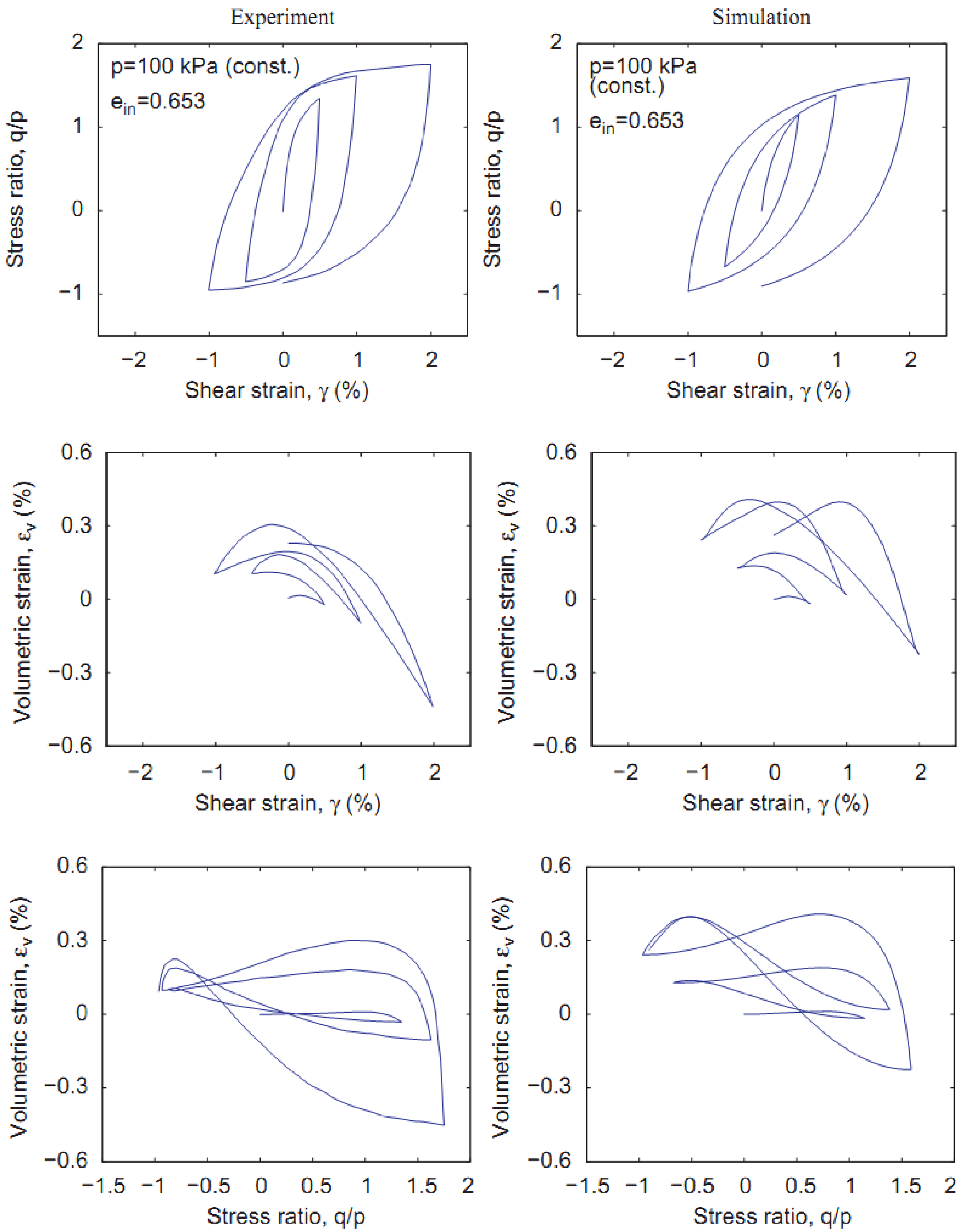

Figure 1: Simulation *vs*. experiments in constant-p cyclic triaxial tests on a relatively dense sample of Toyoura sand [40].

Figure 1 indicates that the shear strain-stress, shear strain - volumetric strain and volumetric-strain stress relationship under experimental condition and numerical simulation [40]. This data could be used for liquefaction resistance prediction.

LIQUEFACTION FORCE FOR LIGHT STRUCTURE STABILITY

The ground flow causes by static gravity force and dynamic force due to seismic acceleration continued sometimes after ending seismic loading [41]. But the liquefied sandy soil micro-mechanical mechanism clearly has not been documented [42]. The realistic soil dynamic liquefaction modeling is complex and requires a multiscale, multiphysics computational framework [43]. The bearing capacity failure of effected sandy subsoil by liquefaction is occasionally occurred during the past earthquakes, and many of structures have faced different types of settlement and damages [44]. There are several techniques for liquefaction mitigation based on different subsoil and geomorphology of affected territory. There is a practical guidance for minimizing ground displacement for designing structures and barriers [45]. For eliminating liquefaction force the compacted gravel piles in loose sandy subsoil have been traditionally used. It is well known that the drainage system reduced destructive liquefaction force [46-48], and stone columns increased soil bearing capacity and reduced settlement [49]. The subsoil materials characteristic is one of the main factors for structure stability. This is a theoretical suggestion on light structure stability through appropriate conquering natural dynamic liquefaction force. A type of sandy saturated semi-confined column has been proposed for conquering dynamic liquefaction forces and improving light structure stability. The model installed beneath the structure for converted loose liquefied area to a strengthened zone. The pore water pressure in saturated confined sand increases column strength. The method is more acceptable and cost effective compare to employing any types of piles. The result expected to have strong correlation between liquefaction resistances, shear forcing and seismic wave propagation of soil seismic mechanical properties. The geometry of sandy column has important role for producing upward pore water pressure. There is practical observation and experimental work is needed for comparing sandy saturated semi-confined column performance with other types of foundations in loose saturated sandy subsoil. The load-settlement behavior was considered to be nonlinear.

In this method a saturated sandy semi-confined column beneath the light structure footing has been constructed, and the sandy column is consist of the

1. Dense semi-confined sand
2. Concrete shell
3. Concrete base plate
4. Holding bar
5. Air valve
6. Underground water
7. Sand morphology

The stress on the stone column is much higher than the stress on the soft soil. Therefore the choice of the proper stiffness, spacing and diameter of the stone columns is very important to improve an existing soft soil [49]. It is observed that as the stiffness of the stone columns increases, maximum settlement decreases, but differential settlement increases [50]. Reducing foundation weight characteristics is advantage of sandy saturated semi-confined columns when the soil is in the liquid state, the sandy saturated semi-confined columns due to containing void among the sands particle has resistivity for submerge and subsequently resulted in reducing settlement. The liquefied sand has very low shear strength and behaviors with maximum settlement and deformation during shaking. The modified sandy saturated layers treat as an elastic solid under un-drained condition. It is expected that the minimum potential settlement and deformation would be occurring when the confined pore water pressure is in maximum level. The model provide the potential for substantial cost reduction and environmental pollution maintaining, due to maximum use of natural sand instate using fully concrete or other manufactured civil engineering materials.

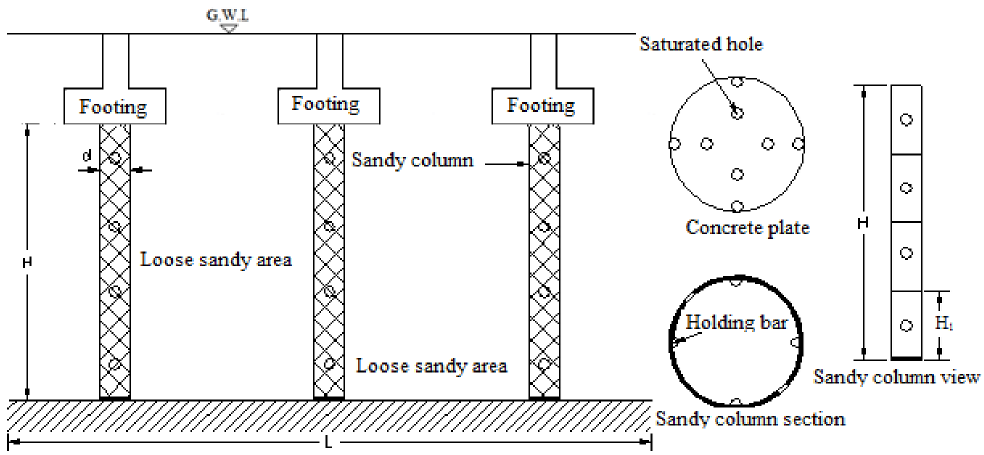

Figure 2: Sandy saturated semi-confined columns used under footing for improving light structure stability

VALIDATION OF MODEL

The structure foundation shown different response in seismically liquefied area and it is complicate to appropriate model due to large variability of seismic data. In this study the earthquake magnitude, frequency, and duration have numerical modeled, to predict semi-confined column behavior. In this numerical simulation the MAT Lab has been used.

The important factors for simulation are as following.

a. Estimating ground motion magnitude, frequency, and duration.
b. Evaluation of liquefaction zone and magnitude.
c. Assessment of critical semi-confined column material characteristics.
d. Analyzing semi-confined column stability due to a scenario earthquake.

FURTHER RESEARCH REQUIRED

There is possibility for predicting earthquake magnitude damage if geophysical site investigation identifies wave propagation behaviour in a subsoil.

The wave magnitude and time travel of one direction and multi direction seismic wave propagation in correlation with liquefaction resistance and pore water pressure in different loose saturated sandy subsoil have to be investigated.

The sandy saturated semi-confined columns has been proposed for conquering liquefaction dynamic forces to improve light structure stability during an earthquake. The model has to be tested under laboratory condition for different sands subjected to the dynamic load.

The seismic wave propagation of nonlinearly frozen soil behaviour has to be investigated in correlation with the wave propagation magnitude and direction.

CONCLUSION

The earthquake behaviour always not same and each earthquake shows unique behaviour characteristics. The earthquake ability and its destructive power are concerned to the several factors. The site geological and geotechnical characteristics is one of the main factors. The soil mechanical properties allow to the seismic wave to be transfer in different shapes and create volumetric strain and stress. There is possibility for predicting earthquake magnitude damage if geophysical site investigation identifies wave propagation in a soil. The one direction dynamic force resultant has more ability in collapsing soil liquefaction resistance. The multi-direction dynamic force characteristic is improved soil liquefaction resistance. Sand morphology controlled seismic wave propagation and re-liquefaction in different depth of loose saturated sandy subsoil.

At final a type of sandy saturated semi-confined column has been proposed for conquering liquefaction dynamic forces for improving light structure stability during an earthquake. The model expected to work in an actual liquefied sandy soil subjected to an earthquake. And destructive force converted to an element for supporting light structure stability due to the saturated loose sand changed to a strengthened zone based on conquering liquefaction dynamic force. It is expected the geometry of sandy column has significant role on producing strengthened zone under light structure. The sandy column weight characteristic has resistivity for submerge and subsequently resulted in reducing settlement of light structure.

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APPENDIX

The earthquake caused excess pore-water pressure, ground movement, sand boiling, deformation, settlement, lateral pressure, landslide, liquefaction, reducing liquefaction resistance, changing wave propagation characteristics due to changing material engineering properties, instability of structures and slope failure etc. To solve these problems the experimental, numerical and simulation research method are required. The level of groundwater and surcharge are important factors in simulation of soil dynamic engineering properties. To simulate earthquake function the shaking table tests is helped many researchers for analyzing seismic infrastructure stability and develop trustable seismic analysis methods.

The soil changing engineering properties mechanism is investigated trough the analyzing shaking table test results. The data recorded form shaking table tests has been used for numerically simulation of subsoil stability behavior during subjected to dynamic force and the material engineering properties is changing according to the dynamic force behavior.

The latest development reconnaissance discovery has been made near precise explanations in soil experimental investigation, although considerably evolution is necessary for understand in summarizing requirement research work and feasible science. The investigation on changing engineering properties of soil requires for predict mitigation of geotechnical engineering problem and the level of settlement, shear strength and bearing capacity of soil. Analyses of soil laboratory experiments help in accurate soil foundation. The nonlinear settlement collapses partially of soil foundation and ended to failure of whole structure. The moisture content is very important issue in engineering properties of soil foundation.

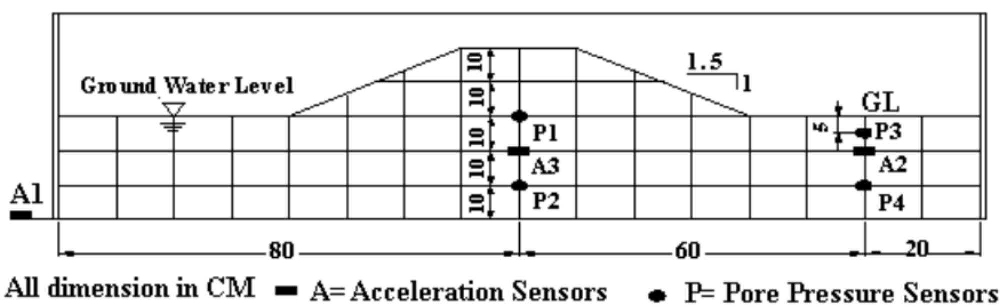

Figure 3: Position of transducer [1]

Soil properties during the shaking under the embankment in the subsoil have been calculated using following formula: where E = Modulus elasticity, $\boldsymbol{\varepsilon}_V$ = Volumetric shear strain, μ = Poisson ratio, σ = Shear stress

$$E = \frac{\Delta\sigma}{\Delta\epsilon}$$

$$\boldsymbol{\varepsilon}_v = \frac{(\sigma_1+2\sigma_3)}{E}(1-2\mu)$$

$$\boldsymbol{\varepsilon}_v = \frac{\Delta V}{V_\circ}$$

Poisson ratio under the embankment during the shaking was μ = 0.42 and Poisson ratio away from the embankment during the shaking was μ = 0.37 [2].

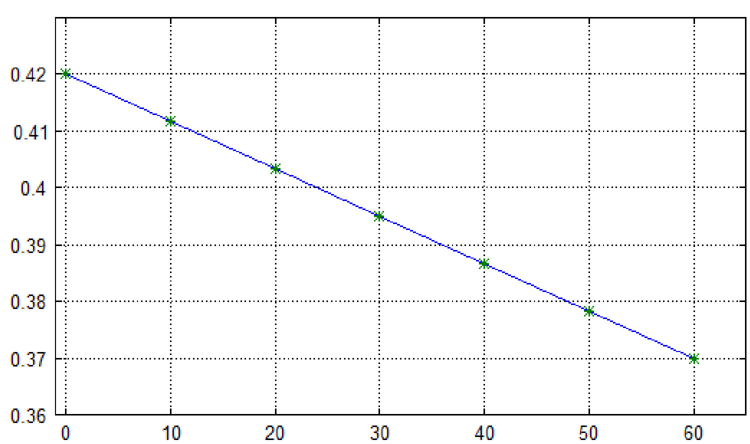

Figure 4: Poisson's ratio of liquefied soil from A3 to A2, during subjected to dynamic force

The liquefaction is depending on pore water pressure geometry and velocity as well as soil engineering characteristics. Figure 2 is shown Poisson ratio recorded by A3 to A2 which are installed in subsoil from beneath the center of embankment and 60 cm away from that. The Poisson ratio was not constant in subsoil at a time. The changing soil engineering properties make a question for accuracy of dynamic stability simulation of embankment. The in numerical simulation the pore water pressure mechanism helps to approach appropriate behavior of model material for realizing stability and finding failure mechanism of embankment. It has been find that the embankment gravity force help in improving Poisson ratio of sandy subsoil. The surcharge force enhanced soil Poisson ratio for cycle of shear stress-shear strain. It is difficult to include concept of changing materials Poisson ratio of liquefied soil subjected to dynamic force in canned program. However the mathematical modeling has to develop for this concept. And also before executing any analysis the extensive experimental and numerical simulation are essential. A useful method for minimizing error is Taylor series to predict a function value at one point in terms of function value and its derivatives at another point in one time.

If the x_i = initial point for measuring any soil engineering properties and $f(x_i)$ is Poisson ratio in x_i location and x_{i+1} = second point for measuring any soil engineering properties and $f(x_{i+1})$ is Poisson ratio in x_{i+1} location, it could express prediction mathematically as

$$f(x_{i+1}) \approx f(x_i)$$

which is call zero-order approximation it mean the value in both point are same or very close to each other. And according to the experimental result is provided in figure 2, it is allowed to estimate of Poisson ratio of soil at different distance. By this additional information it can express this prediction mathematically by

$$f(x_{i+1}) \approx f(x_i) + f'(x_i)\, h$$

which is call first-order approximation it is consist of Poisson ratio $f'(x_i)$ multiple distance h, the expression is capable for predicting an increase or decrease function between x_i location and x_{i+1}. This prediction is for linear trend as the force is dynamic and engineering properties of material change in complicated form it is needed for better prediction. If $f_f'(x_i)$ be measuring Poisson ratio from the pore water pressure graph and $f_b'(x_i)$ be measuring Poisson ratio form acceleration graph the third part of mathematically prediction can express by

$$f''(x_{i+1}) \approx \frac{f_f'(x_i) - f_b'(x_i)}{\Delta x}$$

It can express this prediction mathematically by

$$f(x_{i+1}) \approx f(x_i) + f'(x_i)\,h + \frac{f''(x_i)}{2!}h^2$$

If the $f'_{S1}(x_i)$ is Poisson ratio value of field before applied dynamic force and $f'_{S2}(x_i)$ is Poisson ratio value of field during applied dynamic force and $f'_{S3}(x_i)$ is Poisson ratio value of field after applied dynamic force the second part of mathematical modeling can be express by

$$f^{(3)}(x_{i+1}) \approx \frac{f'_{S1}(x_i) - f'_{S2}(x_i) - f'_{S3}(x_i)}{\Delta x}$$

And R_n =

The complete Taylor series expansion will be;

$$f(x_{i+1}) \approx f(x_i) + f'(x_i)\,h + \frac{f''(x_i)}{2!}h^2 + \frac{f^{(3)}(x_i)}{3!}h^3 + \ldots\ldots\ldots + \frac{f^{(n)}(x_i)}{n!}h^n + R_n$$

$$e^x = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots, \qquad -\infty < x < \infty$$

Calculated during shaking table applied dynamic force on subsoil and embankment.

From other hand in Bernoulli’s equation for the flow has been neglected.

For a steady-state flow of a non-viscous incompressible fluid, Bernoulli’s equation is:

$$h = h_p + h_e + h_v = \frac{u}{\gamma_\omega} + z + \frac{v^2}{2g}$$

where;

Total head (h) = pressure head (h_p) + elevation head (h_e) + velocity head (h_v)

Fluid pressure = u; gravitational acceleration = g; velocity = v;

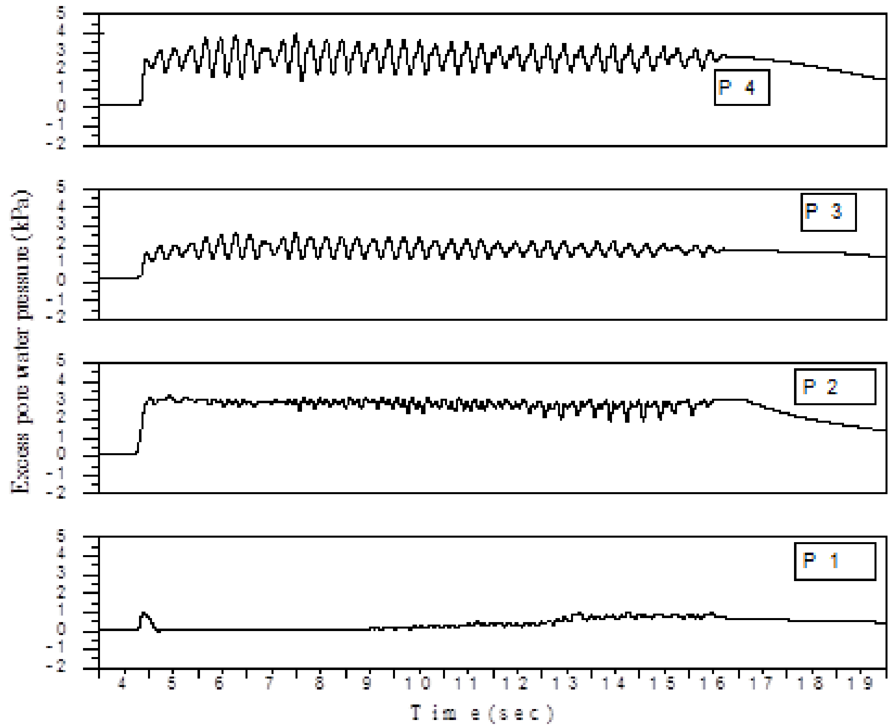

Figure 5: pore water pressure history [1]

The pore water pressure graphs of sensors 1 in figures 3 shown that when shaking table are vibrating the pore water pressure increases. But after the collapse of embankment, the pore water pressure is decreased. And P1 will not record and pore water pressure and later due to over flowing water in surface from seconds' 9 pore water pressures has been recorded again. The dynamic pore water pressure is governed liquefaction resistance and it is possibility for liquefaction resistance reach to minimum level. It is due to changing soil engineering properties in time to time.

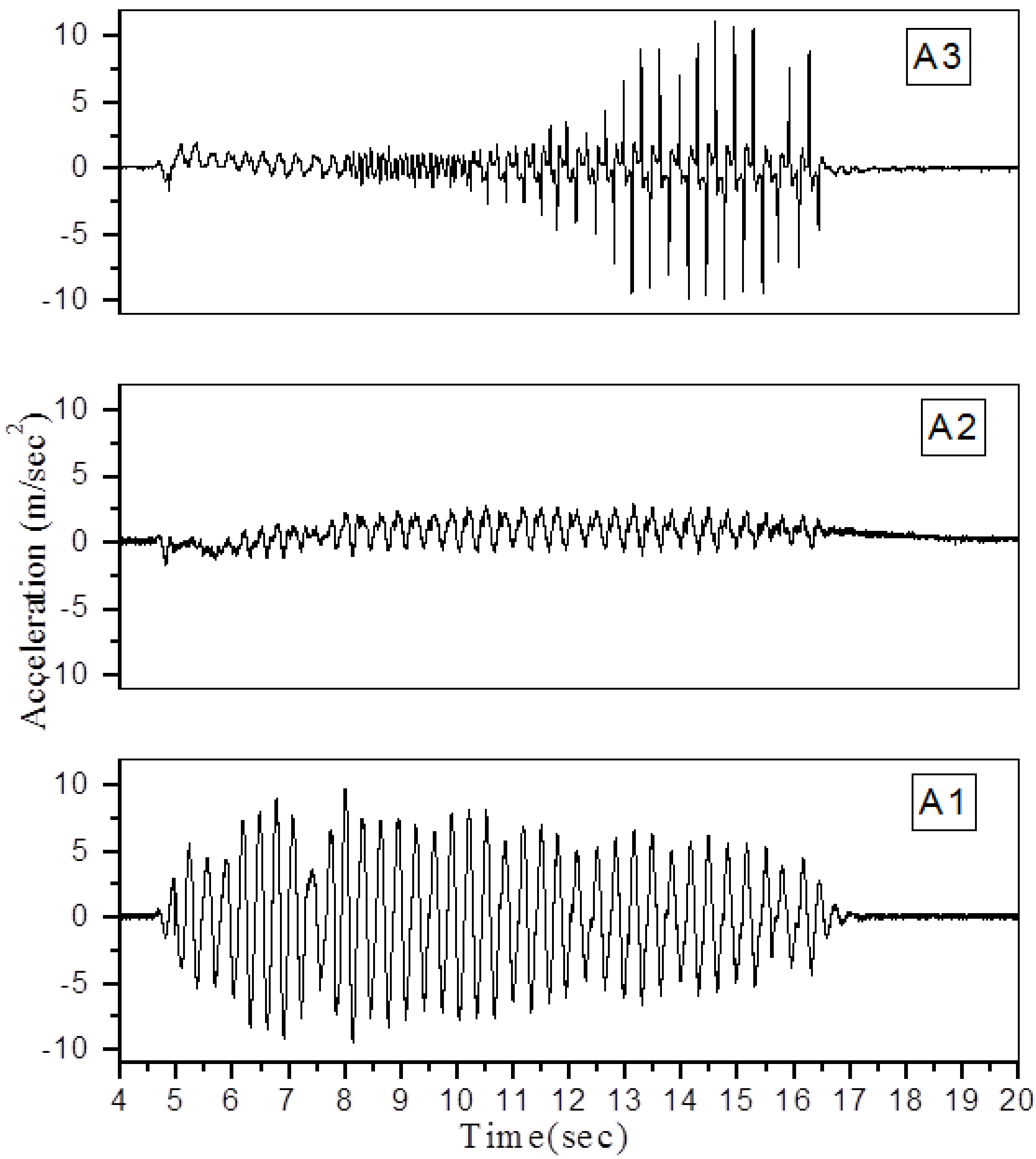

Figure 6: Acceleration time histories in shaking table test [1].

Poisson's ratio = μ; coefficient of lateral pressure at-rest $k_0 = \frac{\mu}{1-\mu}$ (Roy E. Hunt, 2006)

Soil foundation during a strong seismic motion subjected to nonlinearity modification of soil engineering properties and subsequently resulted in easy excessive total stress in fully saturated sandy subsoil. And also in partially saturated subsoil due to negative effect of pore water pressure, the effective stress appeared nonlinearity greater than total stress.

CONCLUSION

In the numerical simulation the pore water pressure mechanism helps to approach appropriate behavior of model material for realizing stability and finding failure behavior of embankment. It has been find that the embankment gravity force help in improving Poisson ratio of sandy subsoil.

It is difficult to include concept of changing materials Poisson ratio of liquefied soil subjected to dynamic force in canned program. However the mathematical modeling has to develop for this concept.

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