EXPERIMENTAL CONSIDERATION ON THE MECHANISM OF LIQUEFACTION

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SUMMARY

The studies after 1995 Hyogoken-Nanbu Earthquake have remarkably developed so many knowledge of liquefaction or behavior of transient ground movement. These aspects have been summarized and applied to the design standards for liquefaction and lateral spreading of ground in Japan. The authors had touched to the design of pile foundations against lateral spreading and felt that those design was on the poor physical basis, in other words, most of design standards have been built up by the inverse analysis or in-situ observation. Actually, the mechanism of liquefaction and its related lateral spreading would not be obvious still now.

At first, experimental works in the past papers were reviewed. The experiments gave us very important aspects to know the mechanism why excess pore water pressure is generated by liquefaction. By the consideration of those experiments, physical meaning of liquefaction was considered as a phenomenon that sand grains sink down in the underground water. This consideration led to an equilibrium equation for sinking of sand grains. Furthermore, equation of a motion of sand grains was given based on the movement of water through void surrounding sand grains.

INTRODUCTION

Studies for liquefaction and disaster associated with it have been developed successfully since more than 30 years ago. Especially, a lot of discussion and investigation have been carried out after 1995 Hyogoken-Nanbu Earthquake in Japan. Huge damages caused by the liquefaction to the important facilities made us to know the needs to build up stricter design standard for liquefaction to save them from collapse. In the most of new standards in Japan, design against the lateral spreading due to liquefaction have been installed. But the mechanism of lateral spreading hasn’t been confirmed yet. Actually, the design methods look like a little bit over estimation of external forces.

A lot of design engineers might feel that the design method for lateral spreading is not likely to rational as the authors thought. Perhaps, the reason is uncertainty for the mechanism of lateral spreading, in addition to obscurity of the mechanism of liquefaction. To find the dominant factors of liquefaction, the authors reviewed past studies for fundamental experiments mentioned in following discussion.

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REVIEW OF FUNDAMENTAL EXPERIMETS

Although, there would be another experimental studies or considerations, these three papers [1][2][3] are enough to know the basis of liquefaction. The Oldest experiment was reported by Florin and Ivanov (1961) [1]. Which was really fundamental experiments and indicated important findings. Scott (1986) [3] referred to Florin and Ivanov and described that excess pore water pressure at a depth in homogeneous ground dissipates linearly depending on time from point A as shown in Figure 1. In this report, the attention was paid to the change of porosity/void ratio from initial state to solidified state after liquefaction. As a result, following two things were summarized implicitly. 1) Sand grains is sinking during liquefaction with constant velocity. 2) Solidification front rise up from the bottom of liquefied layer because of a sand grains in a deeper part of liquefied layer require shorter distance to stop sinking. Kokusho [2] conducted one dimensional liquefaction test similar to Florin and Ivanov. The experiments aimed to know the growth of water film at the boundary between permeable sand layer and worse silt seam. The experiment conducted by Kokusho gave valuable results and a kind of sufficient evidence to the considerations as described in the following discussion. The liquefaction was triggered by the impact in those experiments commonly, and those showed similar distribution pattern of dissipation of excess pore water pressure as shown in Figure 2.

EQUILIBRIUM EQATION FOR SINKING SAND GRAINS

It is familiar that the gradient of excess pore water pressure indicates the unit weight of soil in water; in other words, excess pore water pressure develops into the magnitude of effective overburden soil pressure in the initial state when the layer liquefies completely. Response of excess pore water pressure shows similar gradient to the boiling of sand. The only difference between boiling and liquefaction is whether water is supplied or not. The interaction between sand grains and pore water is considered to be same in both phenomena. It will be easy to understand that sand grains sink in the underground water producing excess pore water pressure. In addition, it should be noted that the motion of sand grains is governed by gravity.

A homogeneous liquefied layer is divided into N thin layers like Figure 3. Each thin layer element of thickness dz are assumed to sink uniformly. Figure 4 shows forces acting on a minute element (dx,dy,dz). To focus on the motion of sand grains, the minute element is divided into sand grains and pore water. It must be noted that the effective stress acting on the sand grains is σ' multiplied by $(1+e)$, where e is void ratio at the initial state of ground. Sand grains are considered to sink down in the underground water, the resistance force due to the viscosity of water must be taken into account. Following equilibrium equation is obtained combining an equilibrium equation of sand grains with that of pore water as follow.

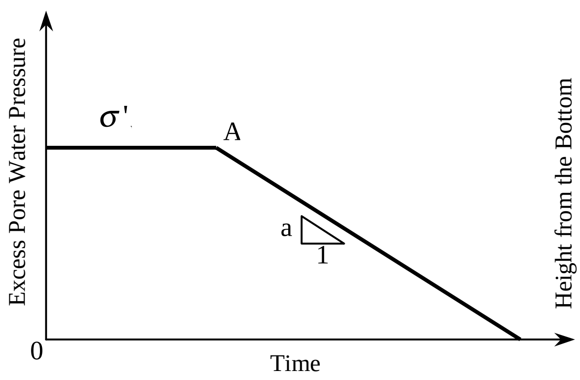

Fig. 1 Typical Pattern of Time History Response of Excess Pore Water Pressure.

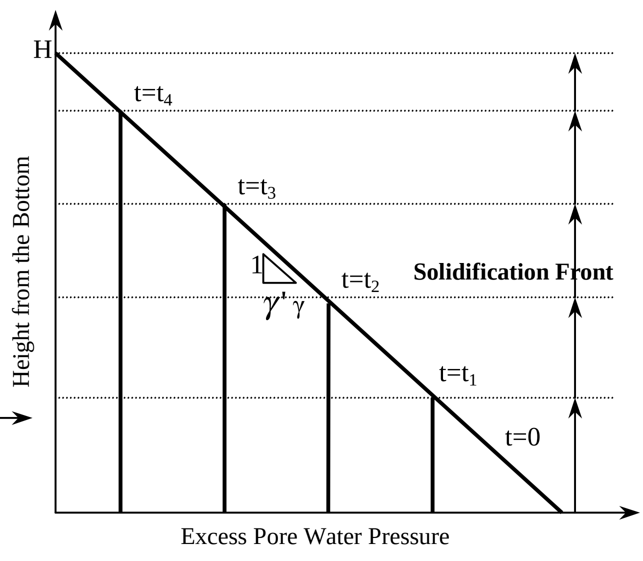

Fig. 2 Typical Distribution Pattern of Excess Pore Water Pressure.

$$\rho_d \frac{\partial^2 u}{\partial t^2} = \gamma' - \left(\frac{\partial P}{\partial z} + \frac{\partial \sigma'}{\partial z} \right)$$

$$Where, \quad \frac{\partial P}{\partial z} = -\frac{P_b - P_f}{dz}, \quad \frac{\partial \sigma'}{\partial z} = -\frac{\sigma'_b - \sigma'_f}{dz} \qquad (1)$$

u is the displacement of sand grains in a minute element from its initial position, ρ_d is dry unit mass of soil, γ' is buoyant unit weight of soil.

Though underground water doesn't flow but grains do sink as a phenomenon, the surrounding water might be regarded as in motion from viewpoint of the grains. To know the velocity of sinking sand grains, void in the minute element can be replaced into cylindrical holes. All the cylindrical void holes have same radius, and total volume of cylindrical void holes is that of soil of the initial ground. Hagen-Poiseuille's Flow is applied to the movement of pore water in the holes. It can be considered that the velocity of sinking sand grains is similar to the mean velocity of Hagen-Poiseuille's Flow. Furthermore, Darcy's Law can be assumed. Noting that the direction of flow is in opposite to sinking of sand grains, following equation of motion for sand grains is obtained.

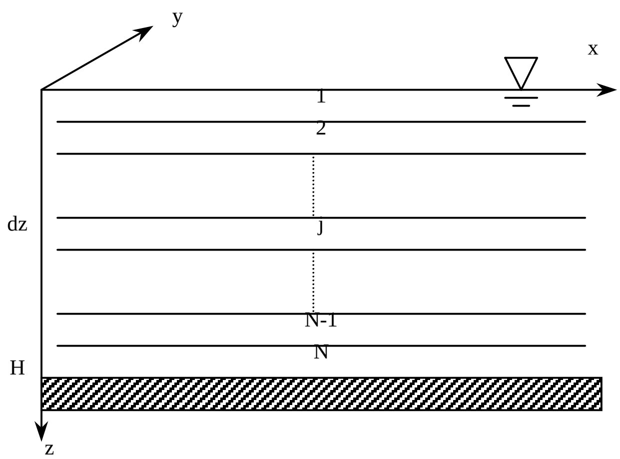

Fig. 3 Simplified Model Ground.

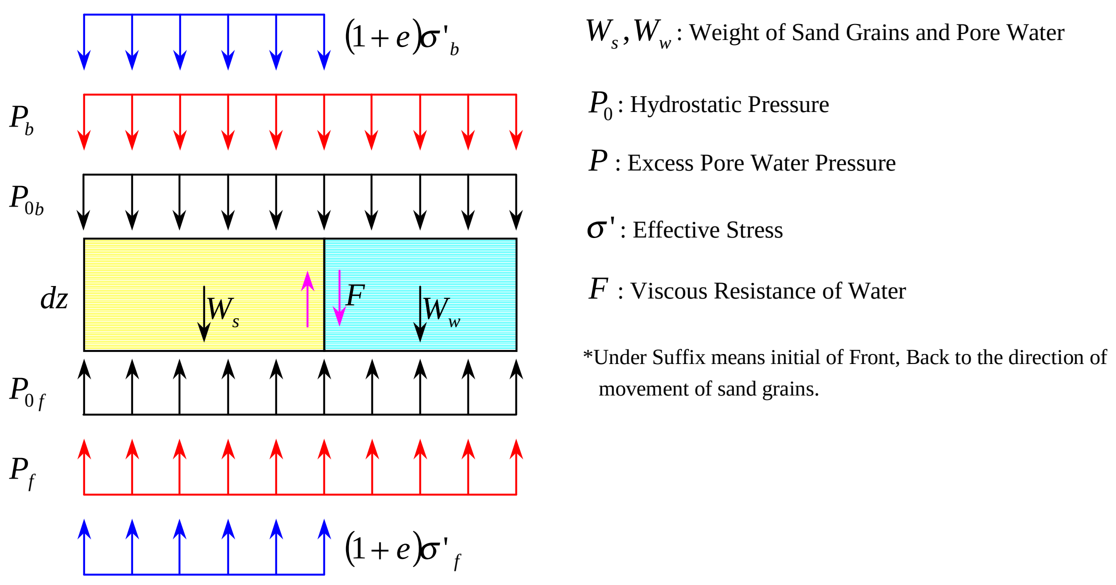

Fig. 4 Forces Acting on the Minute Element.

$$\rho_d \frac{\partial^2 u}{\partial t^2} + \frac{\gamma_w}{k}\frac{du}{dt} - \left(\gamma' - \frac{\partial \sigma'}{\partial z}\right) = 0 \tag{2}$$

Where, γ_w is unit weight of water, and k is coefficient of permeability of soil. After a bit of time, velocity of sand grains becomes constant. How long will it take for sand grains to be constant velocity? As an initial condition for motion of sand grains is that velocity and displacement are equal to zero, there is acceleration due to gravity. Comparing the orders of velocity of sand grains and gravity, the time needed for sand grains to be constant velocity can be estimated about 10^{-5}~10^{-7} second. Generally, it is considered liquefaction continues for some tens minutes. The estimated time is extremely short and negligible. The term of inertia force in Eqs. (1), (2) can be ignored and Eq.(1) can be simplified as follow.

$$\frac{\partial P}{\partial z} + \frac{\partial \sigma'}{\partial z} = \gamma' \tag{3}$$

The velocity of sand grains v in no effective stress is obtained from Eq. (2).

$$v = \frac{du}{dt} = \frac{\gamma'}{\gamma_w} k \tag{4}$$

CONSIDERATION ON THE DISSIPATION OF EXCESS PORE WATER PRESSURE

Equilibrium of sand grains sinking with constant velocity is represented by Eq. (3). According to this equation, the gradient of excess pore water pressure changes with the occurrence of vertical effective stress. The effective stress occurs recovering a contact of sand grains. In this case, it is only considered to recover the contact that sand grains deposits to the bottom of liquefied layer and loose its velocity. Following settlement function can be assumed considering the layer is densified after liquefaction.

$$S(z) = \frac{e - e_f}{1 + e}(H - z) \tag{5}$$

e_f means void ratio of the layer after liquefaction.

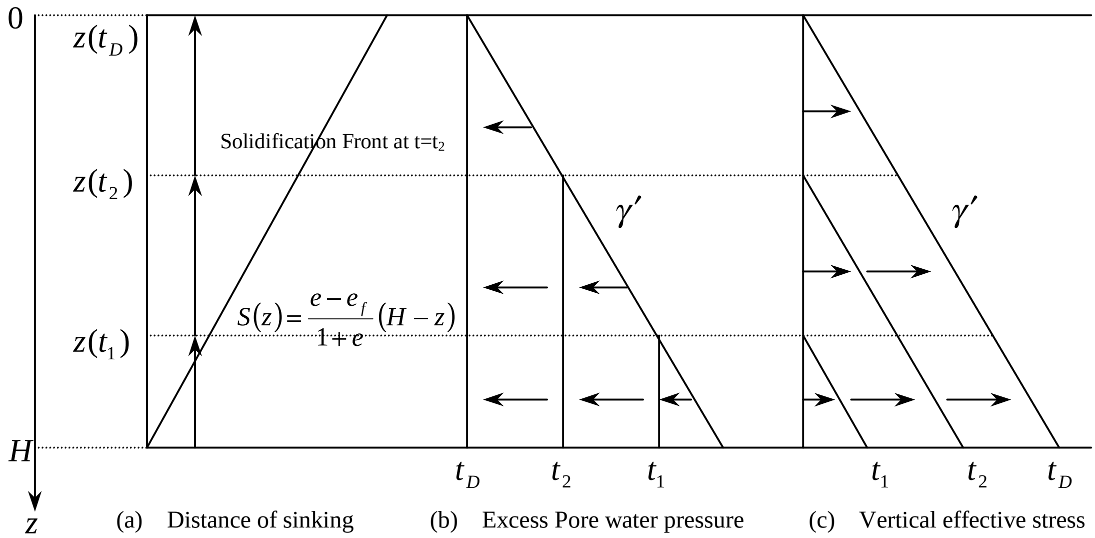

Fig. 5 Distribution Patterns of Excess Pore Water Pressure and Effective Stress Based on the Equilibrium Equation.

To obtain a position of solidification front at a time $t = t$, the speed of sinking sand grains by Eq.(4) and settlement function are applied and the position is expressed as follow.

$$z(t) = H - \frac{1+e}{e-e_f} vt \tag{6}$$

In the solidified part, there exist no longer relative motion between sand grains and underground water, nor gradient of excess pore water pressure (exactly say, there may be an effect of consolidation caused by re-deposition). Figure 5 shows the dissipation of excess pore water pressure and recovery of effective vertical stress based on Eq. (4). Distribution pattern of excess pore water pressure is similar to the past papers like Figure 2. This agreement supports the fact that excess pore water pressure has been developed by sinking sand grains in underground water.

NUMERICAL SIMULATION ON 1-D EXPERIMENT OF LIQUEFACTION

Experiment Conducted by Kokusho

For lack of experiments conducted by authors, the experiment conducted by Kokusho [2] was referred to confirm the above consideration of the mechanism of liquefaction. Figure 6 shows apparatus and test conditions of the experiment. The sand layer is consisted by Toyoura sand, Japanese standard sand, and the model was built by water sedimentation method. The silt seam was existing at the intermediate part of sand layer. Main results of the experiment are shown in Figure 7 and Figure 8. Note that these data were picked and plotted from the original figures in the paper [2].

Simulation by Numerical Approach

Motion of thin layers as modeled in Figure 1 can be solved numerically. Deposition of a thin layer is judged by the relative displacement to lower thin layer. This judgement is based on the assumption that the dry unit mass of soil changes denser after liquefaction. When a thin layer is judged it deposited to the under thin layer, velocity of the thin layer(s) must be modified. If the under thin layer have already lost its velocity, means completely deposited to the bottom of liquefied layer, the thin layer will loose its velocity and effective stress will recover. On the other hands, to simulate the results by Kokusho, it was required to express the deposition of sand layers to silt layer that sinks slower than sand layer. This type of deposition will be called 'semi re-deposition' in following discussion. Thin layers in the group of semi re-deposition, they will sink as one. The velocity of this group can be estimated obtaining the effective stress on the upper boundary of the bottom thin layer in semi re-deposited group.

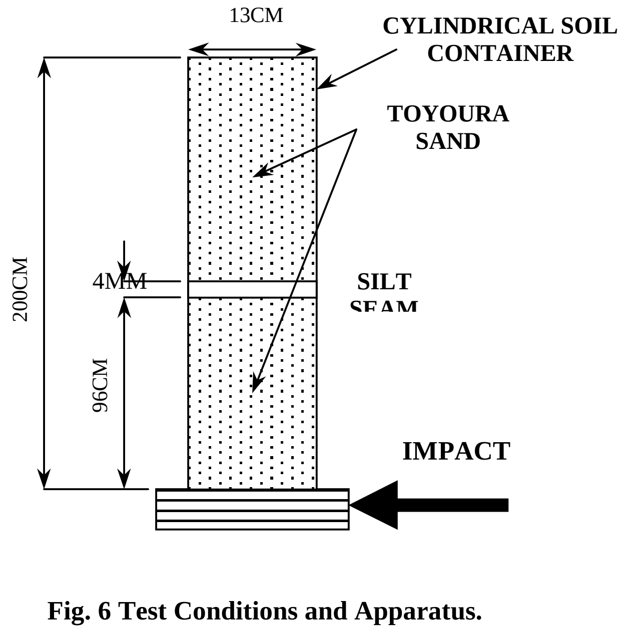

Fig. 6 Test Conditions and Apparatus.
Reference [2]

Coefficient of permeability of the layers were estimated inversely in the simulation. 4.25×10^{-4}, 4.0×10^{-4}, 4.5×10^{-7} (m/sec) were applied to upper sand layer, lower sand layer and silt seam respectively. The results are shown in Figure 9 and Figure 10. They showed good agreement to the results of experiment by Kokusho. In the Figure 9, point A indicates the moment when the top of lower sand layer re-deposits completely, and point B indicates the moment when the top of upper sand layer semi re-deposits on the silt seam. The silt seam and upper sand layer are sinking as one from B to C. Time needed to dissipate excess pore water pressure completely will Strongly depend on the permeability of silt seam. In the Figure 10, qualitative distribution patterns of excess pore water pressure is similar to the result of experiment, especially in upper sand layer. Gradient of excess pore water pressure in solidified part shows zero in lower sand layer. But the level of excess pore water pressure by numerical result doesn't indicate good agreement to the experimental result. It is considered two reasons. One is that the difference was caused by the heterogeneousness of lower sand layer. The other is that the friction between soil container and semi re-deposited part in the upper sand layer.

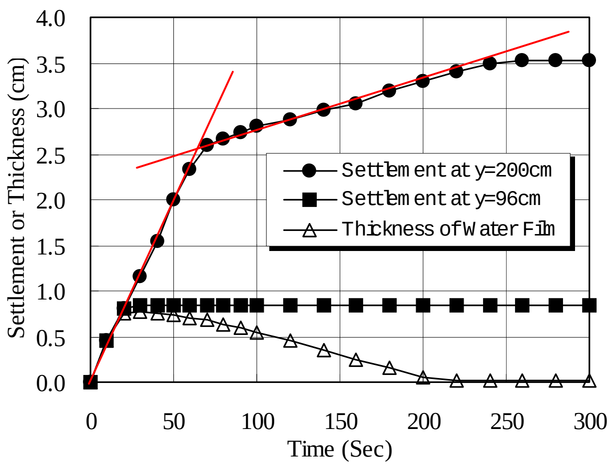

Fig. 7 Time History of Settlements and Thickness of Water Film.
Reference [2]

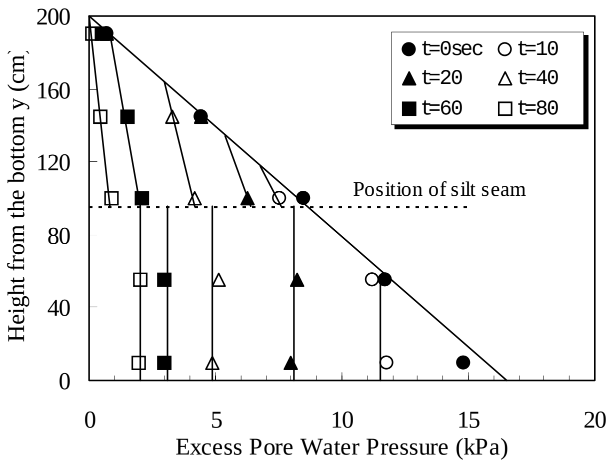

Fig. 8 Distribution Pattern of Excess Pore Water Pressure.
Reference [2]

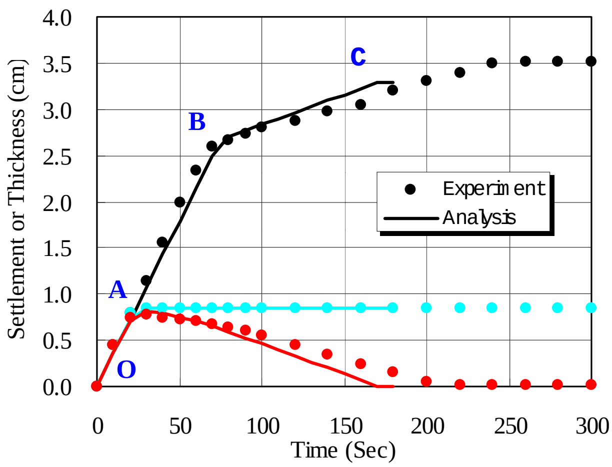

Fig. 9 Numerical Results of Time History Responses of Settlements and
Thickness of Water Film.

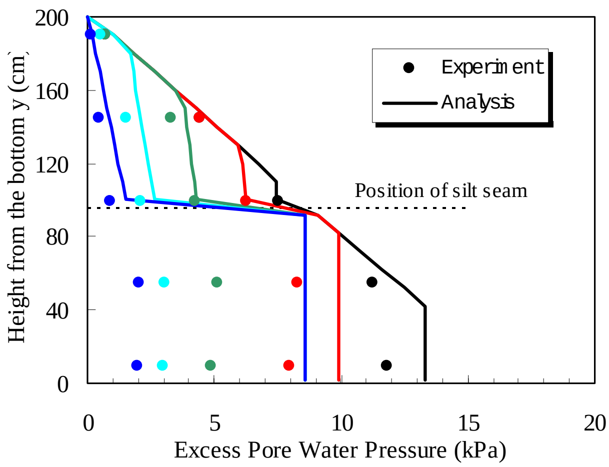

Fig. 10 Numerical Result of Distribution Pattern of Excess Pore Water
Pressure.

CONCLUSIONS

1. Development of excess pore water pressure is caused by sinking of sand grains in underground water.
2. An equilibrium equation and equation of motion for sinking sand grains are obtained assuming Darcy's Law.
3. Sand grains sink with constant velocity as soon as liquefaction occurs.
4. The experiment conducted by Kokusho is well simulated. The mechanism of development and dissipation of excess pore water pressure are clarified by the concept 'sinking sand grains'.

However, some concepts have been proposed such as limit strain for the deformation of liquefied layer or principle of potential energy, these haven't mentioned what kind of force will stop lateral spreading physically. According to the above concept, lateral spreading of ground due to liquefaction will be stopped by re-deposition of sand grains. The amount of the lateral spreading will increase in the process of re-deposition of liquefied layer, and the time required to re-deposit completely is considered very important dominant factor for an estimation of the amount of lateral spreading.

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