27 May 2010, 7:30 pm - 9:00 pm

Determination of the Proper Thickness of Sublayers for Analyzing Post-Liquefaction Deformation Associated with Seepage of Pore Water After Earthquake

Ramez Alchamaa
Tokyo Metropolitan University, Japan

Mitsutoshi Yoshimine
Tokyo Metropolitan University, Japan

Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

DETERMINATION OF THE PROPER THICKNESS OF SUBLAYERS FOR ANALYZING POST-LIQUEFACTION DEFORMATION ASSOCIATED WITH SEEPAGE OF PORE WATER AFTER EARTHQUAKE

Ramez Alchamaa
Tokyo Metropolitan University,
Dept. of Civil & Environmental Eng.
1-1Minami-Osawa, Hachioji,
Tokyo 192-0397, JAPAN

Mitsutoshi Yoshimine
Tokyo Metropolitan University,
Dept. of Civil & Environmental Eng.
1-1Minami-Osawa, Hachioji,
Tokyo 192-0397, JAPAN

ABSTRACT

The estimation of the large flow deformation in the liquefiable layered ground and its effects on a variety of civil structures and infrastructures is considered to be a significant concern in recent earthquakes. This paper proposes a new practical approach for estimating the appropriate thickness of sub-layers within a soil profile (soil element size) for simulating the post-liquefaction deformation considering the seepage flow of pore water after an earthquake. The findings of recent numerical analysis and extensive series of triaxial tests were utilized to develop the ability to analyze such fundamental issue. The study was conducted based on to the large strain deformations and the realistic interaction between inhomogeneous distribution of permeability in ground, volume change of soil due to seepage after earthquake and the extent of lateral deformation in the liquefied soil profile. Toward the goal, the consequential horizontal displacements and the corresponding volume change due to shear localization in soil elements from a series of centrifuge tests conducted by Kulasingam et al. (2002) at UC-Davis were utilized. The volume change of soil element is proved to be primarily related to its potential of shear deformation based on the results of triaxial tests Yoshimine et al. (2006). This strongly suggests that the magnitude of shear localization and its corresponding lateral flow deformation formed directly beneath low permeability soil sub-layer after shaking event are highly affected by the flow and mechanical conditions of the subsoil as well as its geometry.

INTRODUCTION

Post-liquefaction flow deformations of ground persist to be a major part of earthquake related damages in many parts of the world. Experience from past earthquakes indicates lateral spreads and flow slides have been widespread in saturated granular soils in a variety of soil structures such as foundations, highways, embankments, and earth dams. Movements may exceed several meters even in very gentle slopes. More interestingly, failures have clearly witnessed not only during earthquake shaking but also after the end of shaking with delay of few minutes to a day after the earthquakes (e.g. Seed 1979, Ishihara 1984 and Yasuda 2004). The mechanism involved in such large lateral displacements is considered to be not sufficiently understood phenomenon. Sand deposits mostly consist of spatial permeability contrast within the soil medium "surface low-permeability layer(s)" which govern the gradual dissipation of pore water pressure in long term and accordingly form both dilation and contraction zones within the liquefiable sand profile as a result of the change in volume (swelling or compression) due to the upward seepage of pore water after the earthquake. Yoshimine et al. (2006) proposed an empirical and analytical method for estimating the resultant deformation of one dimensional sloped ground considering the possibility of volumetric changes in soil elements within a liquefiable soil profile due to the upward seepage of pore water pressure. The method takes into account the soil behavior under drained condition.

In view of the deformation of the elements located in the dilation zone with the liquefiable soil profile, it is important to predict the influence of the model configuration. Further, based on the findings of this paper, a practical numerical approach for handling and determining the appropriate size of element in a model ground analyzed in 1Dscene was developed.

The predicted deformation magnitude for a homogenous liquefiable slope with various initial relative densities and a variety number of discrete of sub-layers (thickness of the divisions within the liquefied layers) was investigated through the scale effects on soil behavior; a model of fully liquefied sub-soil profile with impervious sub-layer soil profile was analyzed linearly taking into account the consequent flow deformation and volumetric changes due to upward seepage throughout its elements.

INFLUENCE OF LAYER DIVISION OF THE LIQUEFIED SUBSOIL PROFILE ON THE LATERAL DEFORMATION

This section presents and discusses the results of analyses conducted to investigate such impact on the resultant deformation. Considering an idealized case of a fully liquefied soil layer with an impervious sub-layer (k = 0) at the top and bottom of the ground model, as illustrated in Fig. 1. a.

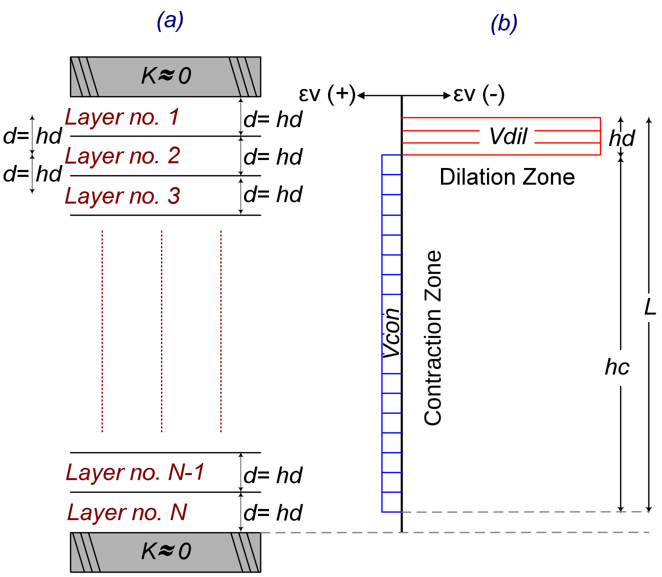

Fig. 1. (a) Fully liquefied sub-soil profile with impervious sub-layer and its model used in analyses, (b) distribution of volumetric strain throughout the soil layers.

The post-liquefaction seepage in soil elements within a model ground is associated with the shear deformation is shown in Fig. 1.b. When the excess pore water starts to dissipate from the lower portion of a liquefied soil profile after the end of shaking, the volume of pore water V_w and the rate of pore water flow v_n will be constant throughout the soil elements within the homogenous subsoil profile, as shown in Fig.2. Moreover, since the permeability coefficient within the sub-layers below the impervious layer is identical ($k_n=k_{n-1}$), no volumetric change is expected to occur until the excess pore water pressure is dissipated in the lower portion. Therefore, a contraction zone will develop gradually from the bottom layer toward the upper sub-layers along with the dissipation of the pore water from the soil elements.

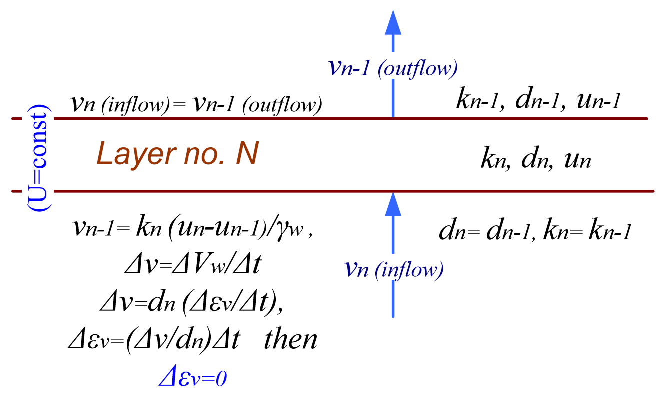

Fig. 2. Profile of the liquefied sub-soil with impervious sub-layer and its model for seepage analysis and the flow conditions.

What is more, that the contrast in permeability coefficients between the liquefied layers and the impervious layer at the top of the liquefied layer, the top sub-layer of the liquefied layer at a near distance to the interface between the mentioned layers and due to the absorbed volume of water within this zone from the lower sub-layers a dilation zone near the interface will be formed as well with a thickness of h_d as seen in Fig.1. The generated thickness of dilation zone is adopted to be the thickness of the sub-layers of a stratified layer of liquefied sand. In general cases of upward seepage flow, the volumetric strain $\varepsilon_{v,n}$ of Nth layer can be calculated at any moment using the equations:

$$\varepsilon_{v,n} = \int \frac{v_n - v_{n-1}}{d_n} dt \qquad (1)$$

The rate of upward seepage of water v_n can be calculated from:

$$v_{n-1} = \frac{d_n + d_{n-1}}{d_n / k_n + d_{n-1} / k_{n-1}} \times \frac{u_n - u_{n-1}}{\gamma_w} \qquad (2)$$

Where u_n in the excess pore water pressure of Nth layer, d_n is the thickness of of Nth layer. Additionally, the formulation of the shear strain caused by volume expansion due to pore water seepage based on the experimental relationship between maximum principal strain ε_1 caused by volumetric strain ε_v, can provide a useful tool in this concern. Yoshimine et al. 2006 simulated this relationship approximately using the following formulas:

$$\varepsilon_{v,ult} = \frac{(e_{\max} - e_{\min})(D_{r,ult} - D_{r,ini})}{1 + e_{\max} - (e_{\max} - e_{\min})D_{r,ini} / 100} \qquad (3)$$

$$\varepsilon_1 = 2.5(D_{r,ini} - D_{r,ult})\left(\frac{1}{\varepsilon_v - \varepsilon_{v,ult}} - \frac{1}{\varepsilon_{v,ini} - \varepsilon_{v,ult}}\right) \qquad (4)$$

where $\varepsilon_{v,in}$ is the initial volumetric strain which is required to trigger the flow deformation, a constant value of $\varepsilon_{v,ini}$ = 0.5% is adopted from the test results. The minimum and maximum void ratio of Toyoura sand are $e_{\min}$ = 0.597 and $e_{\max}$ = 0.977, respectively. $D_{r,ult}$ is the relative density at steady state at infinite shear deformation. In case of Toyoura sand, the void ratio at steady is about 0.93 in lower stress levels (Verdugo & Ishihara 1996), therefore, $D_{r,ult}$ =12.4% is adopted and the volumetric strain at steady state ($\varepsilon_1 = \infty$) is obtained by Eq. 4.
Furthermore, as the soil elements are in plane strain mode where $\varepsilon_2 = 0$ and the volumetric strain ε_v equals to the normal strain on the surface, the shear strain due to seepage analysis γ_s can be expressed by:

$$\gamma_S = 2\sqrt{\varepsilon_1(\varepsilon_1 - \varepsilon_v)} \qquad (5)$$

The volume of dilation zone, V_{dil} which expresses the volume of the dilating sub-layer can be estimated from Fig. 1.b. since the total thickness of the homogenous sub-layers below the impervious sub-layer, $L=Nd$, where N is the number of divisions within the liquefied layer, d is the thickness of a sub-layer or division within the liquefied sand below the impervious layer in (m).
The thickness of the dilating sub-layer within the liquefied sand can be determined by assuming that the volume of the contraction zone is equivalent to the volume of the dilation zone as follows:

$$V_{dil} = V_{con} \qquad (6)$$

Where V_{con} the volume of the contraction zone, therefore the condition becomes:

$$\varepsilon_{dil} = -\varepsilon_{v,\max}(N - 1) \qquad (7)$$

ε_{dil} is The amount of volumetric strain at the top of liquefied sand layer (the interface between the tow layers), assumed to be equal to the maximum volumetric strain due to consolidation following liquefaction, $\varepsilon_{v,max}$. Ishihara and Yoshimine.(1992) proposed $\varepsilon_{v,max}$ to be mainly a function of relative density. As a result, the lateral displacements at the top of the liquefied sand layer directly below the impervious layer can be calculated can be calculated from Eq. (1) to (7).
The result of analyzing the model ground in Fig. 1.a. with a total thickness of liquefied layer, L=1m reveals that the volumetric change of sand during deformation is strongly affected by the initial density of the material. Very dense sand with initial relative densities ranging from 80 to 100% appears to swell much more water to dilate and show signs of large shear deformation. Fig.3 suggests that when sand is looser, a very small number of divisions, N within the liquefied layer is enough to form a large flow deformation.

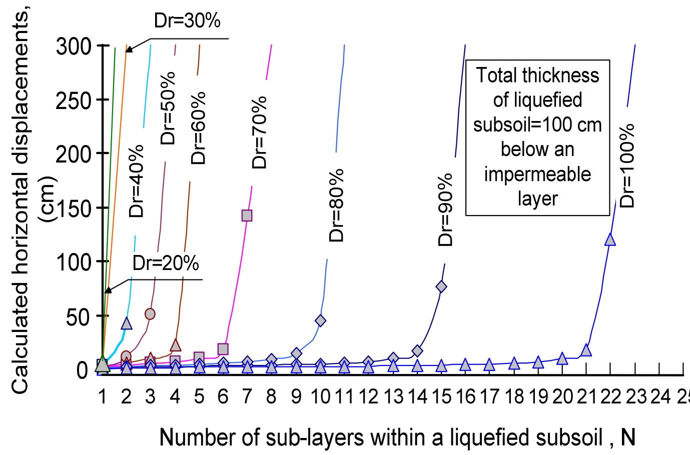

Fig. 3. Horizontal displacement vs. number of sub-layers, N within a liquefied subsoil with total thickness of 1m below the impervious layer for a verity of initial relative densities.

COMPARISON OF THE ANALYZED MODEL GROUND WITH THE PREVIOUS CENTRIFUGE MODEL TESTS DATA

In order to investigate the proper thickness of sub-layers within soil profile as a function of relative density and total thickness of the liquefiable layer, the results from a series of five centrifuge tests conducted by Kulasingam et al. 2000&2001) at UC-Davis were chosen for 1-D numerical analysis of the volume change and the corresponding flow deformation considering the seepage flow of pore water pressure due liquefaction.
A series of centrifuge tests, namely, (RKS02~ RKS11) was carried out by Kulasingam et al. (2001) at UCD to study the effects of void redistribution on liquefaction behavior of layered soils; typical model configuration of centrifuge using the 1-m radius Schaevitz centrifuge with rigid container of 560 x 280 x 180 mm is shown in Fig. 4.
The above-mentioned centrifuge tests modeled a 1:2 (v:h) submerged slope in prototype scale of homogenous Nevada sand of with a range of relative density from 30 to70%, with non-plastic silt arc. Kulasingam et al., (2001) demonstrated that a slope model of Dr = 20% without a silt sub-layer can resist the applied shaking event whereas a similar model with greater relative density e.g. 50% failed when a silt layer (contrast in permeability) is present in the slope.

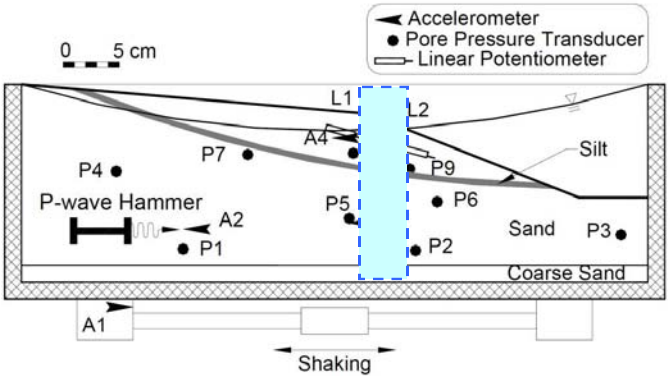

Fig. 4. General model configuration and instrumentation layout for series of centrifuge tests, namely (RKS02~ RKS11) after Kulasingam et al. (2002).

The displacements parallel to the silt arc was measured and then converted in prototype units. Some limitations of recorded data from tests (RKS02, RKS04 RKS09, and RKS11) were reported by Kulasingam et al., 2002, due to several reasons such as the displacement measurement target near the middle of slope at L2 (see Fig.4) came off the soil after shaking, in some events, the settlement measurement plate at L2 got buried in the following mass of soil or sudden changes in recording displacement because of electronic noise. For this reason, the digital records of results from the mentioned four model tests were not used in this study herein. Alternatively, the lateral displacements parallel to the silt arc were measured manually from the video images (see Fig.5.) after various motions (shaking events), namely A, B and C where the strain localization was observed clearly in the mentioned model tests near to free surface of the slope (Fig.4 & 5), these soil columns highly represent the condition of the infinite slope and suitable for 1D seepage analysis. As seen in Fig. 7. The free surface of slope appeared to be in full Parallel to the sliding surface due to the resultant shear deformation.

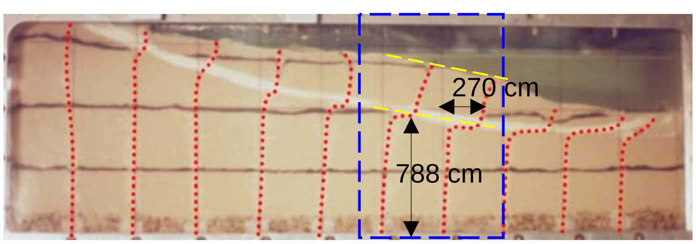

Fig. 5. Photo from test RKS05 (Dr≈35%, Sand with Silt Arc) shows the strain localization and the measurements of the total thickness of subsoil below the silt arc and the displacement parallel to the silt arc (modified after Kulasingam et al. 2002).

The measured horizontal displacements just blow the silt arc were plotted as seen in Fig. 6. A bounding line was fitted between the scattered data for different relative density and shaking events. The general trend of the bounding line was formulated and extended for sands with higher and lower relative densities as illustrated in Fig. 6. The centrifuge model

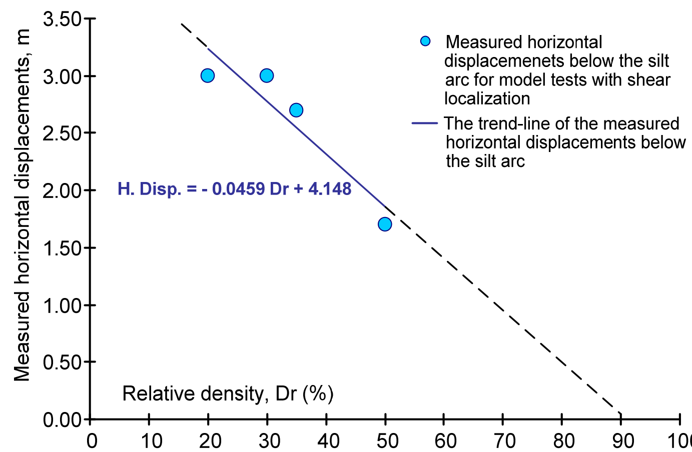

Fig. 6. Measured horizontal displacements vs. relative densities for the events of strain localization occurrence as data from centrifuge model tests.

as a soil profile in prototype scale and the appropriate number of sub-layers within the liquefiable sand to satisfy the measured lateral displacements was investigated for a range of initial relative density between 20 to 100% as shown in Fig. 6. The total thickness of the liquefied subsoil below the silt arc was measured to be 7.88m. as shown in Fig. 5.

Tests data was analyzed using the model ground in Fig. 1.a.wi th L=7.88m. Fig.7. reveals that very dense sand with relative density ranging from 80 to 100% have very low potential for generating flow deformation or shear localization in the dilation zone. One may notice that there is no effect for the number of discrete within the liquefied layer on the possible deformation. Therefore, any small number would be sufficient for such dense soils. In contrast, the very loose sand was found to have high potential to generate flow deformation, as the magnitude of deformation elevate to infinity if the number of divisions is larger than 1, which means that such soils are not in need to be divided into smaller sub-layers and considering it as one layer would be sufficient regarding the resultant magnitude of deformation. This behavior can be seen obviously from Fig.7. For sand with relative density less than 30%, there is no need to divide the subsoil into divisions and The original thickness of the sub-soil would be sufficient.

Where the sand with higher relative densities, namely from 40 to 70% show a moderate influence with number of divisions ranging from 2 to 5, respectively. The very dense sand showed nonresponsive to the increment in the number of sub-layer as it has low potential for flow deformation, so that a small number of sub-layers would be enough for seepage analyses.

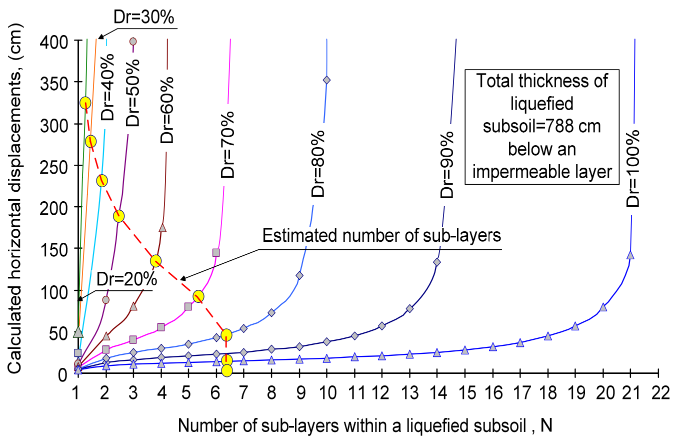

Fig. 7. Estimated number of sub-layers within the liquefied sand as a function of the relative densities and the total thickness of liquefied sand.

Toward the goal, a new practical approach for choosing the appropriate thickness of the sub-layer within a liquefied sand profile for numerical modeling of the resultant flow deformation is presented in Fig.8.

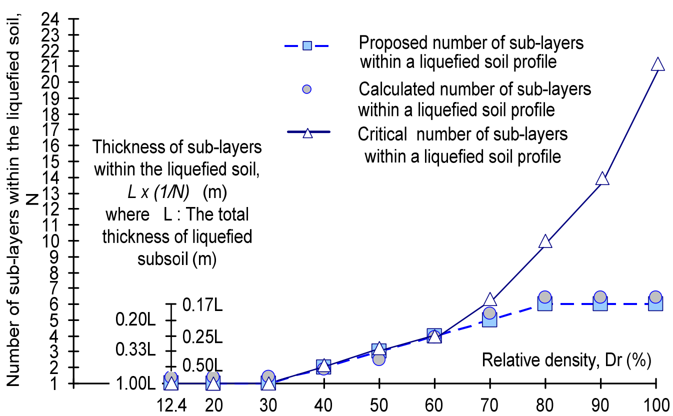

Fig. 8. Proposed number and thickness of the sub-layers within liquefied sand depending on the relative Densities and the total thickness of liquefied sand.

SUMMARY AND CONCLUSIONS

An analytical study was made in this paper to draw attention to the importance of considering sub-layers within the liquefied sand. The permeability coefficient and its contrast within the soil medium are found to take place in controlling the shear deformation and the corresponding post-liquefaction deformation after the end of earthquake shaking. More interestingly, that the analytical investigation of the effect of relative density on flow deformation after the end of the shaking indicated that the trend of shear deformation after the end of shaking can be captured in centrifuge tests and that the Setting of the size of the sub-layers in the analysis is a key factor to estimate accurately the possible magnitude of deformation

The results presented herein emphasis that the number of division within the liquefiable sand is strongly dependant on the initial relative density of the sand. If the relative density of the deposit is less than 30%, the suitable number of sub layer is just one, ie. The number of sub-layer is ranging from 2 to 5 for deposits with medium dense from 40 to 70%, respectively. Where the deposits with higher density from 80 to 100 %, it was found that it is not affected with the number of sub layers as the magnitude of deformation increases slightly with the increment of the number of sub-layers. Moreover, in such deposits the extended trend-line of the lateral displacement versus the relative density from the centrifuge model data reveals a very small amount of deformation. Thus, 6 layers for such deposit are sufficient.

Choosing unsuitable number of sub-layers of dividing a liquefiable soil profile may lead to a mistake in estimating the realistic possible flow deformation due to seepage of pore water and the corresponding volume change in soil elements.

REFERENCES

Ishihara, K. 1984. Post-earthquake failure of a tailings dam due to liquefaction of the pond deposit. *International Conference on Case Histories in Geotechnical Engineering*, St. Louis 3: 1129-1143.

Ishihara, K. & Yoshimine, M. 1992. Evaluation of Settlements in Sand Deposits Following Earthquakes, *Soils and Foundations* 32(1): 173-188.

Kulasingam,R.2001. Malvick, E. J. Boulanger, R. W. and B. Kutter, L.2002.EFFECT OF VOID REDISTRIBUTION ON LIQUEFACTION BEHAVIOR OF LAYERED SOILS: CENTRIFUGE DATA REPORT FOR TESTS RKS01 – RKS11. *REPORT NO.UCD/CGMDR-02/01*

Seed, H.B.1979. Considerations in the earthquake-resistant design of earth and rockfill dams. *Geotechnique* 29(3): 215-263.

Yasuda, S. 2004. Evaluation of liquefaction-induced deformation of structures. Ansal. A (ed). *Recent Advances in Earthquake Geotechnical Engineering and Micro-zonation*: 199-230.

Yoshimine, M., Nishizaki, H., Amano, K. & Hosono, Y. 2006. Flow deformation of liquefied sand under constant shear load and its application to analysis of flow slide of infinite slope. *Soil Dynamics and Earthquake Engineering* 26(2-4): 253-264.

Verdugo, R. & Ishihara, K. 1996. The steady state of sandy soils, *Soils and Foundations,* 36(2): 81–92.