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Paper No. 1024. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

INITIAL STRESS EFFECT ON RESPONSE OF LEVEL GROUND

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ABSTRACT

Effect of the initial stress on the dynamic response of a level ground is discussed. After showing that conventional stress-strain models for one-dimensional analysis do not consider anisotropic initial stress state, a hysteresis rule for a multi-dimensional constitutive model is suggested to explain experimental fact. Then the existence of the initial shear due to anisotropic initial stress state is shown to be a predominant factor even for the level ground. It is shown through numerical examples, however, after subjected to a large earthquake or several earthquakes of same magnitude, the existence of the initial shear does not become important because result of the dynamic analysis converges to the one under isotropically consolidated stress state. This explains the fact that structures in the young deposit such as artificial fill suffers significant damage due to earthquakes compared with old deposit. It can also be concluded that conventional one-dimensional analysis is valid for old deposit which has been subjected to repeated earthquakes, but is not suitable to be used in the analysis of the young deposit which was not suffered by a large earthquake in past.

KEYWORDS

earthquake; nonlinear; response analysis; initial stress; anisotropy; Masing rule; hardening function

INTRODUCTION

Soil exhibits strong nonlinear characteristics even at small strains. For this kind of material, it is well known that initial stress state as well as past loading history affect the subsequent behavior. This condition, however, has not been considered in many dynamic analyses. Shear stress-shear strain relationships schematically shown in Fig. 1(b) have been used in the conventional analyses; hysteresis curve is symmetric about the origin under cyclic loading. Since soils are usually in an anisotropic stress state even in level ground, there exist initial shear. Therefore use of this kind of hysteresis curve may not be able to justify. Probably, one of the main reason why this kind of model has been used is that it seems to be in consistent with the nonlinear characteristics expressed as so called G-γ and h-γ relationships, where G is shear modulus, γ is shear strain, and h is damping ratio. Reports by Yamashita and Toki (1994) and Yasuda et al. (1994), in which G-γ and h-γ relationships are shown to be identical both under isotropic and anisotropic initial stress state if confining pressure is kept the same, also seems to support the use of this kind of model in the dynamic response analysis of level ground.

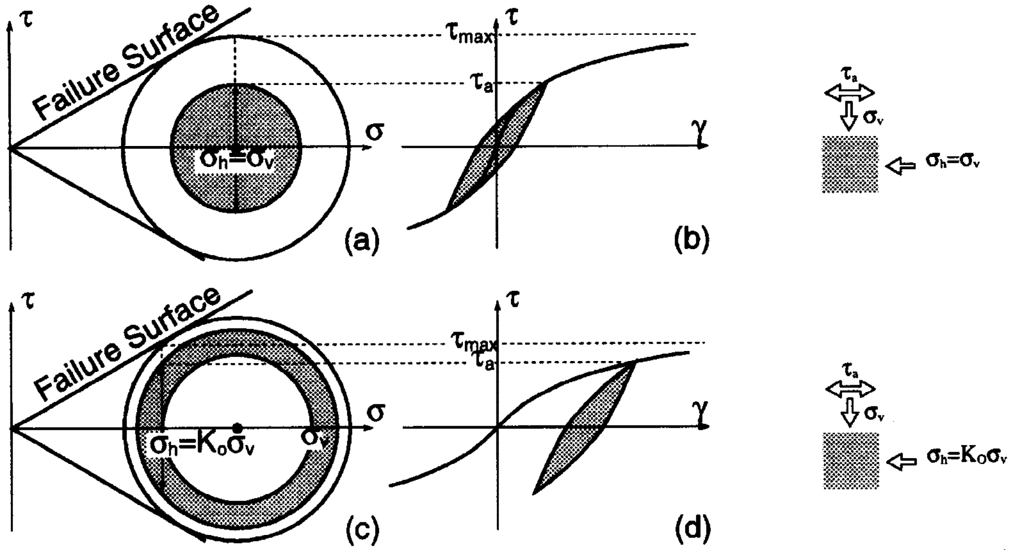


Fig. 1 Schematic figure of Mohr's circle and stress-strain relationships subjected to cyclic load under isotropic initial state and anisotropic initial state.

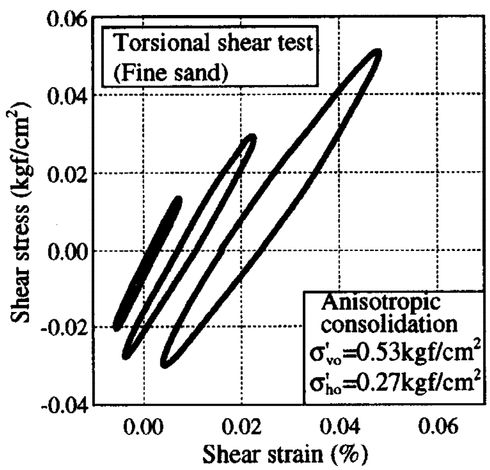


Fig. 2 Hysteresis loops used to compute G-γ and h-γ relationships.

The author has pointed out several questions on G-γ and h-γ relationships to be used in the dynamic response analysis (Yoshida, 1995). The problem in using this kind of stress-strain curve is shown in the paper. The behavior of soils subjected to cyclic shear under the simple shear condition is schematically shown in Fig. 1: (a) and (b) under isotropically consolidated initial stress state (IS condition, hereafter), and (c) and (d) under anisotropically consolidated initial stress state (AI condition, hereafter). Under AI condition, stiffness at the virgin loading is smaller than the elastic modulus because of the existence of initial shear. After unload, however, since stiffness starts from elastic modulus, hysteresis loop under cyclic loading drifts toward the direction of initial loading as shown in Fig. 1 (d). Reports by Yamashita and Toki (1994) and Yasuda et al. (1994) is supposed to just indicate that shaded hysteresis loops in Figs. 1(b)(d) are identical; since shear modulus G is computed from the slope angle of the segment connecting the unload points, the location of the hysteresis loop is not countered. Figure 2 is an example of hysteresis loops from which G-γ and h-γ relationships are computed in the report by Yasuda et al. (Yasuda, 1994), which clearly indicates that the above discussion is true. Under this background, the author discusses constitutive models for the dynamic response analysis and examine the effect of the existence of initial shear on the result of dynamic response analysis in this paper.

HYSTERESIS RULE IN STRESS-STRAIN MODEL

In order to make the discussion simple, the effect of the dilatancy is neglected; only shear deformation characteristics are discussed. Therefore mean stress does not change. Figure 3(a) shows stress path in the deviatric stress plane (s_x-τ_{xy} plane, where $s_x=\sigma_x-\sigma_m$) under simple shear condition; loading starts from A and continues passing the points A→B→C→D→B. If loaded under IS condition, the resultant hysteresis curve will be like that in Fig. 3(b); it is symmetric about the origin. In the case of AI condition, since there exists initial shear at the initial state (point A), stiffness at virgin loading (A→B) is smaller than that under IS condition. Constitutive models for 1-dimensional analysis, such as hyperbolic model and R-O model, cannot express this process; they gives curve AB in Fig. 3(b) regardless to the anisotropy of initial stress. Therefore, these models are not suitable to be used even in 1-dimensional analysis when initial stress is in AI condition. Exterior circle in Fig. 3(a) is an yield locus when stress point reaches to B. Formulation during A→B is almost similar in many constitutive models in multi-dimension. The value of the hardening parameter H at B is denoted as H_B in the followings.

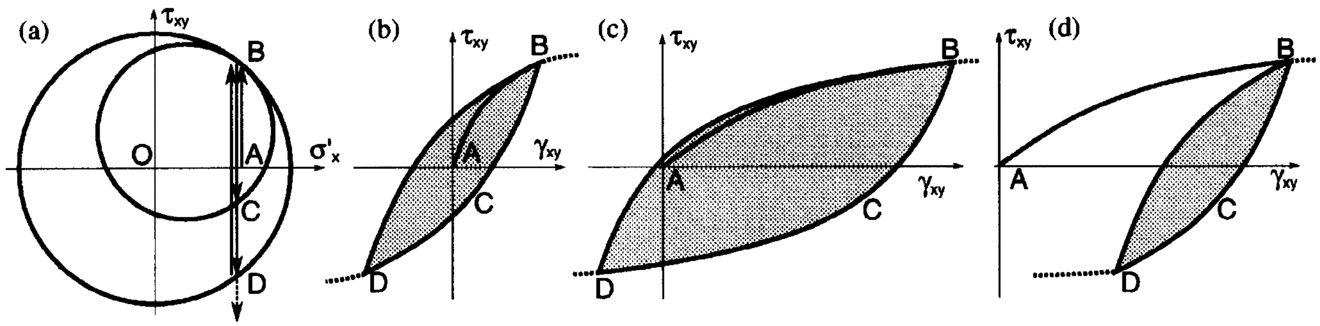


Fig. 3 Behavior under constant load; (a) Stress path (anisotropic stress state); (b) Isotropic stress state; (c) Anisotropic stress state (type-1); (d) Anisotropic stress state (type-2)

The treatment after unloaded from B depends on constitutive models. Roughly, rules under cyclic loading is classified into two types. The value of H starts from 0 (or other values) in both types of model. In the first model, it again reaches to H_B at point D where subsequent yield locus coincide with yield locus at virgin loading (exterior circle in Fig. 3(a)) (type-1 rule). Therefore, if loading continues in the same direction passing D, the slope of the stress-strain curve is continuous at point D as shown in Fig. 3(c) as dashed line. In the same manner, when stress point reaches point B after reloaded from D, the value of H again becomes H_B. Therefore, slopes at point B along A→B and D→B are the same. This types of model gives good looking stress-strain curve because the slope is always continuos except at unloaded points.

The second types of rule (type-2 rule) frequently appears when a constitutive model employs Masing rule in terms of (deviatric) stress (ratio). In these models, H is defined as a function of the distance between unloaded and current points in the stress plane. Since the distance between B and D in Fig. 3(a) is shorter than the diameter of the exterior circle, slope of the stress-strain curve does not continuously change at point D as shown in Fig. 3(d) when loading continues toward the same direction from B to D as shown in Fig. 3(d). In the same manner, slope at point B along D→B is larger than the one along A→B.

Physically, the difference of these rules can be recognized as the difference of independent variable to compute hardening parameter. In point C on path B→D, for example, H is computed as a function of the diameter of the subsequent yield locus (interior circle in Fig. 3(a)) in the type-1 rule. On the other hand, it is computed as a function of distance between B and C in Fig. 3(a) in the type-2 rule. It is obvious that both kinds of model will give the same stress-strain curve A→B in Fig. 3(b) if initial state is origin in Fig. 3(a) or in IS condition. Reports by Yamashita and Toki (1994) and Yasuda et al. (1994) indicate that both slope of segment BD and area of hysteresis loops are identical both under IS and AI conditions. By comparing Figs. 3(b)-(d), it is clear that the type-2 model can explain their results.

In the following calculation, the simplified practical model proposed by Yoshida and Tsujino (1989) is employed, which is similar to Duncan-Chang model (Duncan and Chang, 1970), but extended to multi-dimensional problems and for arbitrary backbone curve and damping characteristics. The model was originally employs type-1 hysteresis rule, which is modified to type-2 rule. Stress-strain curves in Fig. 3 is drawn based on this model.

IMPORTANCE FOR CONSIDERING INITIAL STRESS STATE

In order to show the importance in considering the initial stress state, a dynamic response analysis is conducted. A fill land along the Tokyo Bay area is chosen. Detailed soil investigation are conducted at the site, which includes PS logging at every 25 cm by both downhole and suspension methods, and dynamic deformation tests of the undisturbed samples for every 10 cm distance as well as ordinary borehole investigation. Soil profiles of the site is shown in Fig. 4. The N-S component of El-Centro 1940 records is scaled to a half and used as an outcrop motion at the base. Two analyses are conducted; one under IS condition and the other under AI condition. The coefficient of earth pressure at rest K_0 is taken to be 0.7 for AI condition. Here, the setting of reduced input earthquake motion and larger K_0 value works in such a way that shear strain decreases. Since test to obtain G-γ and h-γ relationships was conducted up to shear strain of order of 1%, a more reasonable setting (large earthquake or small K_0 value) will produce strains much larger than measured strain, which may result in an inaccurate result. A constitutive model proposed by Yoshida and Tsujino (1989) is used in the analysis, in which backbone curve is expressed as a piecewise linear function whose secant shear modulus coincide with G-γ relationships obtained by test, and curve after unload is selected so that hysteretic energy absorption coincide with h-γ relationships. Figure 4 shows peak response values and Fig. 5 shows stress-strain relationship at 9th layer (GL-8 to 9 m). Here α_{peak}, δ_{peak}, τ_{peak} and γ_{peak} denote peak values of acceleration, displacement, shear stress and shear strain, respectively.

Analysis under IS condition exhibits larger acceleration and shear stress, but smaller displacement and shear

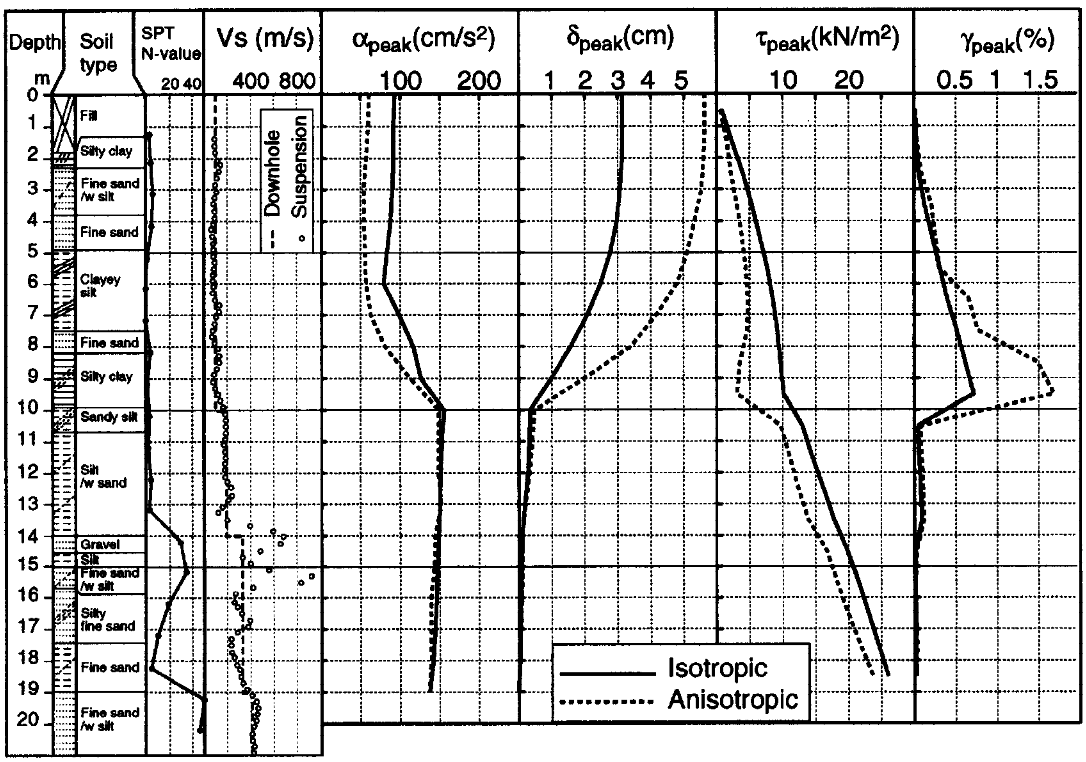
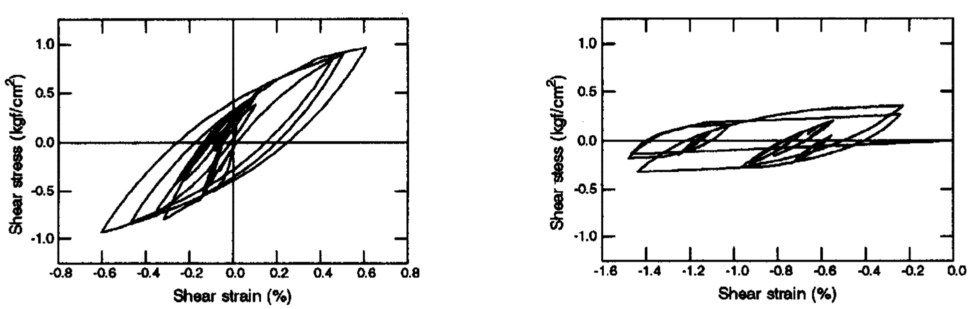


Fig. 4 Soil profiles and peak response values



(a) Isotropic consolidation (b) anisotropic consolidation

Fig. 5 Stress-strain relationships at 9th layer strain compared with the analysis under AI condition. The reason becomes clear when looking at Fig. 5. Because of the existence of initial shear in the analysis under AI condition, both stiffness and strength is smaller in the analysis under AI condition than IS condition. As a result, nonlinear behavior becomes predominant in the soft soil from GL- 6 to 10 m. Shear wave does not propagate through this layer causing shear stress larger than strength, which is the reason why acceleration and shear stress under AI condition is smaller. On the contrary, shear strain and displacement becomes larger in these layers because of strong nonlinear behavior. As seen in Figs. 4 and 5, the difference of the results in two analyses is large, therefore consideration of initial stress state is important.

NUMERICAL EXAMPLES AND DISCUSSIONS

As shown in the previous section, the stiffness in the virgin loading is smaller than elastic modulus if there exists initial shear or anisotropic initial stress state. This arises some questions. For examples, does shear wave velocity measured by PS logging represent the elastic wave velocity? The answer is yes. Shear strain amplitude due to PS logging is very small. Probably, there were ground shakings in past which produced shear strains comparable to this amplitude, therefore soils are at the state just after unloading, i.e., elastic state. Then what happens under a large earthquake? In this section, the effect of repeated large earthquakes is investigated though numerical analysis of model ground by comparing the behavior of ground with the one under IS condition.

The ground with 10 m deep surface deposit is chosen as a model ground. Shear wave velocity is 100 m/s, internal friction angle is 35°, unit weight is 1.8 t/m3, water table coincide with the ground surface, and coefficient of earth pressure at rest, K_0, is 0.5 in the case of AI condition. In the analysis under IS condition, initial stress state is set so that confining stress becomes the same with AI condition analysis. Hyperbolic model is used for hardening function. The shear wave velocity at the base is set for 400 m/s. The N-S component of the El-Centro 1940 record is employed as an outcrop motion at the base (called large earthquake hereafter). A half of this motion is also used in the analysis (called small earthquake hereafter).

Effect of Past Large Earthquake

Three analyses are conducted under the small earthquake. The first analysis is conducted under IS condition (case-1), and the second analysis is conducted under AI condition (case-2). In the third analysis, small earthquake is applied after applying a large earthquake under AI condition (case-3). Peak response values obtained by these analyses are shown in Fig. 6. Stress-strain curves at the 10th layer (GL-9 to 10 m) where peak shear strain is the largest are shown in Fig. 7. Here, it is noted that stress-strain curve of case-3 (Fig. 7(c)) is moved along the horizontal axis so that the curve starts from the origin although there is residual strains due to previous analysis under large earthquake (see next subsection for the analysis under large earthquake).

Firstly, let follow the behavior in case-2 (Fig. 7(b)). Beside small strain range, path from O to A is in virgin loading, therefore stiffness is smaller than those under IS condition. Path from A to B is in unload process. Path after B is again in virgin loading, therefore, magnitude of shear stress at points A and B are the same. The same procedure occurs along path C→D→E. Magnitude of shear stress is larger at C and D than at A and B because exterior yield locus expanded during the loading process from B to C. The reason of the appearance of kink at B and D are already explained. After unloaded at E, there is no shear stress that exceeds shear stress at E, therefore discontinuous change of slope do not appear in the stress-strain curve.

Similar to the result in the previous section, difference between cases 1 and 2 (IS and AI conditions) is large. On the other hand, difference between cases 1 and 3 is very small. Peak acceleration and peak shear stress by these analyses cannot be distinguished in Fig. 6 although little difference in peak displacement is observed. Moreover, stress-strain curves in Figs. 7(a) and (c) are quite similar although little difference may be found under detailed comparison. This is recognized because the whole behavior in Fig. 7(c) is in

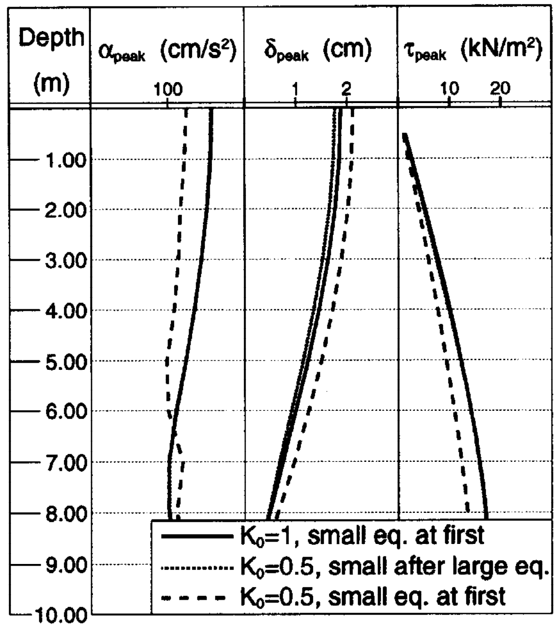
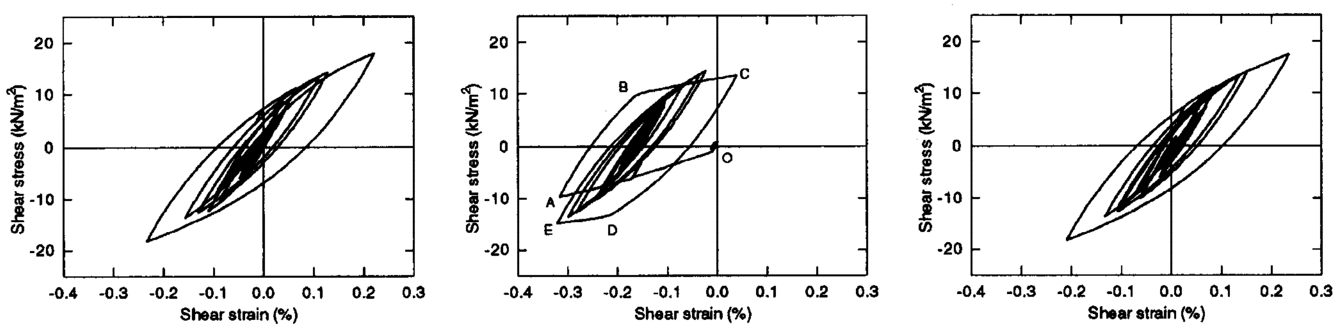


Fig. 6 Peak response under small earthquake



(a) case-1 (b) case-2 (c) case-3

Fig. 7 stress-strain relationships under small earthquake

unloaded or reloaded process and is not in virgin loading process because of the previous large earthquake.

The result of this section indicates that effect of initial shear (AI condition) on the dynamic response is large under first earthquake, but it is negligibly small if the ground was subjected to a large earthquake in past. This also indicates that conventional 1-dimensional analysis in which effect of initial shear cannot be considered is also valid when analyzing an old deposit where there were large earthquakes in past.

Effect of Repeated Earthquakes

Effect of repeated earthquakes is investigated in this section by applying large earthquakes to the model ground repeatedly under AI condition. In total 5 large earthquakes are applied. In addition, analysis under IS condition is conducted for the purpose of the comparison. Figure 8 shows peak response values and Fig. 9 shows stress-strain curves at the 10th layer (GL-9 to 10 m). Again, stress-strain curves after the second earthquake are moved so that it starts from the origin. Since residual strains are positive except at first earthquake, actual shear strain gradually increases toward positive direction under repeated earthquakes.

Same as previous analyses, difference between IS and AI conditions is large, which is needless to discuss here. The difference from the result of the previous subsection appears at the time of second earthquake; the result in the previous analysis was almost the same with the analysis under IS condition whereas they are still quite different in this analysis. The difference between first and second earthquakes are also large; shear strains is predominant in negative direction in the first earthquake whereas in positive direction in the second earthquake. The shape of hysteresis curves are also different. However, stress-strain curves after second earthquake are fairly similar to each other.

Unlike the previous subsection, the magnitude of the second earthquake is as large as first earthquake, therefore, behavior in virgin loading occurred in the second earthquake whereas it does not occur in the analysis in the previous subsection. This is clearly seen when strain firstly increases from about 0.4% in Fig. 9(c). This stage is the same stage in path B→C in Fig. 7(b). Because this stage occurs when shear stress exceeds past maximum shear stress, this region becomes smaller after subsequent earthquakes. Accordingly, shear stress increases. By looking at Fig. 9 (c) to (f), one can recognize that stress-strain curves gradually reaches to the one under IS condition which is shown in Fig. 9(a).

When looking at Fig. 8, one can see that peak displacement decreases and peak shear stress increases due to repeated earthquakes. They gradually approaches to the response under IS condition. On the other hand, there seems some scatter in the response of peak acceleration. Detailed investigation, however, will show that it also approaches to the response under IS condition. The scattering probably comes from two reasons. The first one is that acceleration is the most sensible response. The second reason comes from the

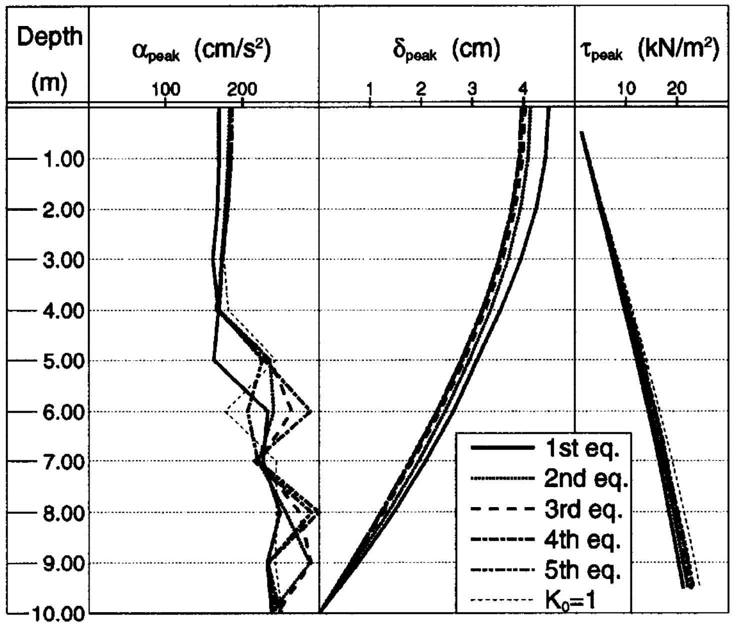
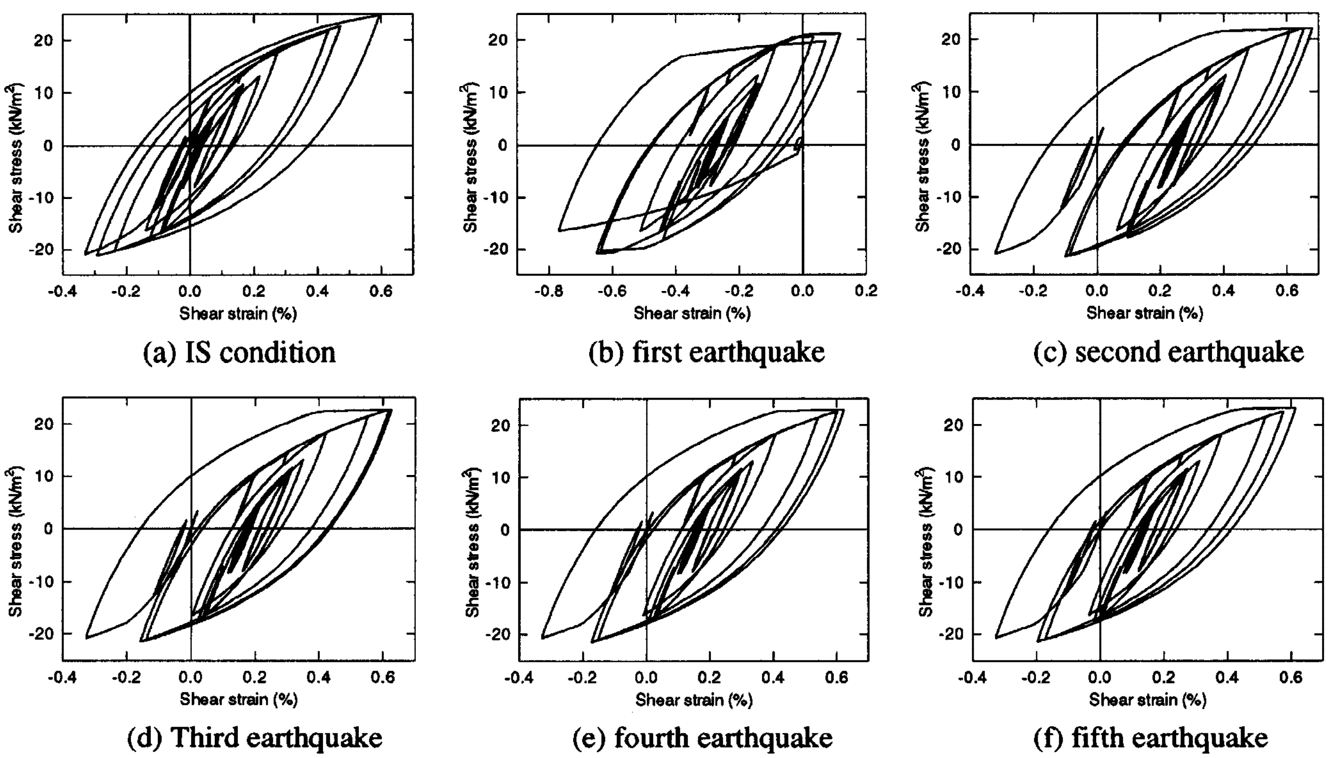


Fig. 8 Peak response under repeated earthquake



(a) IS condition (b) first earthquake (c) second earthquake

(d) Third earthquake (e) fourth earthquake (f) fifth earthquake

Fig. 9 Stress-strain relationship under repeated earthquake propagation of shear wave and response near shear strength. If, for example, peak shear stress at 10th layer increases as seen in Fig. 8, shear wave will propagate through 10th layer more than before. As a result, a more significant nonlinear behavior occurs in the layers above. Therefore, for example, although virgin loading process appears only in positive directions in 10th layer, it may appear in both direction in the layer above. The appearance of virgin loading process will affect the behavior of the adjacent layers and will affect the acceleration response.

Numerical study shown in this section indicate that the effect of anisotropic initial shear appears significantly when virgin loading process appears in the response. Therefore it is very important to consider initial stress state for the young deposit such as artificial fill even for one-dimensional analysis. When virgin loading process appears, shear strain becomes large although acceleration becomes small. This tendency can explain the frequently observed fact on the damage of fill at the time of earthquake, i.e., damage to structures in the fill is usually larger than that in the old deposit. However, after subjected to repeated earthquake, appearance of virgin loading process decreases, and therefore behavior approaches to the ground with isotropically consolidated state although there still exist stress anisotropy.

CONCLUSION

Effect of initial stress on the dynamic response of level ground is investigated through numerical analysis. The following items are obtained as conclusion.

1) In order to explain the report by Yamashita and Toki (1994) and Yasuda et al. (1994), hardening parameter in the cyclic behavior is to be defined as a function of the distance between the current stress and stress at unload in the stress plane.
2) Difference between the response of the ground under isotropically and anisotropically consolidation is very large when the ground is subjected to the earthquake at first.
3) Since conventional stress-strain relationships for one dimensional analysis cannot consider stress anisotropy, it is not appropriate to use it when existence of initial shear affects the response very much.
4) Once subjected to a large earthquake, the behavior of the ground under anisotropically consolidated stress state subjected to the smaller earthquake becomes quite similar to the response of the ground under isotropically consolidated stress state.
5) The response of the ground under anisotropic initial stress state finally approaches to the response of the ground under isotropic initial stress state when subjected to repeated earthquakes with similar magnitude. The change from first to second earthquake is significant, and then deference gradually diminish.
6) The behavior shown in this paper can explain the fact that young deposit such as artificial fill suffers more damage than old deposit. Conventional one-dimensional analysis may be applicable to the old deposit but not for the young deposit which did not suffer large earthquake in past.

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