Critical Influence Parameters of Dynamic Deformation of Unsaturated Loess and Its Application in Magnitude Estimation of Residual Strain

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SUMMARY:
Large seismic loadings may cause unsaturated loess the residual strain, the one of challenge problems in geotechnical earthquake engineering field. The author first investigated critical influence parameters by analyzing physical process and mechanical mechanism of the dynamic deformation. Contrast with laboratory data of dynamic triaxial tests, we then proposed a magnitude estimation method with two associated formulas applied these parameters. Finally, our results show that the residual strain could be regarded as the consolidation response of generalized solid-phase-media (GSPM) of loess under seismic loadings. Here, critical parameters include two aspects, the strength and volume characteristics of GSPM and the seismic loading features. The strength represented endurance capacity to seismic loadings is figured by cohesion and internal friction angle; whereas the volume reflected compression capacity due to under-compacted status is described by void ratio. This work would be helpful to establish the reasonable/practical constitutive model of unsaturated loess under external loadings.

Keywords: unsaturated loess, dynamic residual strain, influence parameter, stress ratio, magnitude estimation

1. INTRODUCTION

Loess is a kind of uniform, cohesive and wind-blown sediment within Quaternary period (Liu, 1985; Terzaghi et al, 1996). True loess deposits have never been saturated and its cohesion is due to the presence of a binder that may be predominantly calcareous or clayey. On saturation the bond between particles is weakened and the surface of the deposit may settle. Meanwhile, natural loess can suffers another obvious settlement under strong seismic loadings, so called dynamic residual deformation or seismic subsidence (Wang et al, 2003). Based on investigational results of earthquake survey and laboratory dynamic test, above plastic deformations due to different external actions may have relations with physical characteristics of more void and weak cohesion of unsaturated loess.

During the early stage to investigate engineering behaviours of natural loess, the collapsibility became the main concerned problem in geotechnical practices (Feda, 1966; Gao, 1980; Lei, 1987; Miao et al, 1999; Rogers et al, 1994; Wang et al, 1982). After the concept of seismic subsidence of loess was proposed in 1980s, the dynamic residual deformation attracted more attention of scientists and engineers in the research field of geotechnical earthquake engineering (Wang et al, 1993). As a result, the loess dynamics has become a thriving topic (even a new research field) in the family field of geotechnical earthquake engineering. For deformation behaviours of natural loess, however, the problem of collapsibility has been known around the world, but efforts onto the relative later issue (dynamic residual strain) is so not enough that the corresponding knowledge cannot probe deeply into the essence of things as before. Especially for the basic problem of dynamic residual deformation of unsaturated loess, critical influence parameters are even indistinct, needless to say its plastic constitutive relation under seismic loadings (Wang et al, 2003).

As a typical unsaturated soil, natural loess could suffer an obvious residual strain while dynamic loadings are large enough to destroy the intrinsic structure strength of the soil. This means there is an initial magnitude of dynamic stress for the dynamic residual strain or seismic subsidence of unsaturated loess. During the early research period of dynamic residual strain of loess, influence parameters have attracted more attention. Unfortunately, influence efforts focus on the strength change associated with single factor, e.g. water content, void ratio, density, modulus of elasticity, and consolidation pressure. The seismic loading feature, meanwhile, is another focal point, e.g. vibration times, loading types, predominant period, effective duration and peak value. For the dynamic residual deformation of unsaturated loess, characteristics of soil mass and seismic loading features are coequally essential. However, the previous effort does not analyze the deformation based on the physical process and mechanical mechanism of dynamic residual strain of natural loess (Deng et al, 2007; Wang et al, 1993; Wang et al, 2007). These analysis results are unreasonable to acquire the knowledge of critical influence parameters because previous concerned factors are dependent each other, for example, the structure strength has relation with all of those factors of water content, density, modulus of elasticity and consolidation pressure. The work, therefore, can not distinctly disclose the physical relationship between dynamic residual deformation and critical influence parameters (structure strength and under-compacted status) of unsaturated loess under strong seismic loadings.

The author, here, first investigated critical influence parameters by analyzing physical process and mechanical mechanism of the dynamic residual deformation of natural loess. We then proposed two relations of three-phase (air, water and solid) volume deformation and void dynamic deformation, combining to describe dynamic behaviours of unsaturated loess under seismic loadings. The first reveals a theoretical relationship of dynamic residual strain, compression value of void ratio and initial void ratio, and the second shows an empirical relationship of compression value of void ratio, structure strength, consolidation pressure and seismic loading based on test data of untrimmed loess samples in laboratory. This work reported by authors would be helpful to establish the reasonable/practical constitutive model of natural loess under external loadings.

2. METHODOLOGY AND LABORATORY DATA

2.1. Analysis of critical influence parameters

2.1.1. Generalized solid-phase-media (GSPM) of unsaturated loess

At unsaturated condition, the natural loess is a special kind of three-phase media with air, water and solid. Generally, the water in unsaturated loess can be divided into two portions. The one of absorbed water contributes to the structure strength of the soil mass due to interface force between water and solid; on the contrary, the other of gravitational water may decrease the strength by dissolved/destroyed the cohesive structure among solid particles.

For unsaturated loess, solid particles and absorbed water jointly constitute the generalized solid-phase-media (GSPM) according to the concept of generalized suction pressure (Shen, 1996). The generalized suction pressure ignores the cause of structure strength of soils, e.g. suction, cohesion or friction, and takes different forces as the same kind of action to resist external loadings. Thus three reasonable phases of unsaturated loess include air, gravitational water and GSPM. By means of this treatment, the analysis of physical-mechanical mechanism of dynamic residual strain of unsaturated loess may become easier than the independently considering case.

The contact of GSPM particles of natural loess is continuous, and other phases of air and gravitational water completely fill the space within the particles. In any loading case of external static/dynamic forces, GSPM can directly respond to external loads, but other phases indirectly bear the additional actions transmitted by GSPM particles. As analyzed physical-mechanical mechanism and critical influence parameters of dynamic residual strain of unsaturated loess, therefore, GSPM is certainly the principal element, whereas the others both are relatively secondary.

2.1.2. Physical-mechanical mechanism and critical influence parameters of dynamic residual strain

During the generational process, three phases of air, gravitational water and GSPM form original mechanical features of unsaturated loess in natural/certain stress conditions. While external static/dynamic forces exert, the phase of GSPM begins adjusting its structure to adapt the change of additional interior stress. Then other phases of air and gravitational water could suffer various mechanical effects with the adaptability adjustment of GSPM under additional forces.

We suppose that GSPM particles of soil mass cannot be broken under any normal external force, which means generalized solid particles keep the same physical shapes. In the ideal stress condition (no external loads except gravity), initial status of arrangement and interactivity of GSPM does never alter. At the beginning of elastic deformation, the change of initial status accordingly occurs; and if interior adjustments of space and stress throughout go under the endurance of the weakest point of unsaturated loess, the elastic strain will continually develop. Otherwise, the plastic deformation will happen, and gradually develop while more and more structural weak points of soil mass are wrecked. At a certain stress condition, wreck points could thread together, and then fracture planes appear within the interior of soil mass. If the plane reaches the natural boundary of unsaturated loess, the soil may be separated. Generally, the deformation response of unsaturated loess under static loads is a phenomenon of consolidation, whereas the dynamic residual strain is one of essential problems in the additional stress due to seismic loadings. From the view of deformation, the dynamic residual strain of unsaturated loess could be regarded as a special kind of consolidation.

As mentioned above, the development process of deformation of unsaturated loess adapted external additional loads includes 5 stages, i.e. initial period, elastic period, elastic-plastic period, plastic period and separation period. The initial period is ideal and only introduced to understand the response mechanism of GSPM structure under external loadings. During the elastic period, the structure strength of soil mass could be never influenced due to the definition of elastic deformation. For plastic period of soil mass, the plastic deformation is absolutely preponderant and the structure strength of soil could suffer an everlasting damage. Once the deformation reaches separation period, the separation soil could not effectively respond external loadings. In this case, the soil basically loses its structure strength. For the unsaturated loess, the dynamic residual strain mainly undergoes the front 4 stages barring the separation period.

The mechanical behaviour of unsaturated loess under external loadings is jointly influenced by GSPM and other phases. During the deformation process, actions of other phases on GSPM distinctly tend to vary within different stages. We suppose the void of unsaturated loess is completely filled by air and gravitational water, and the deformation only has relation with the space compression due to wracked structures. In the initial period, the deformation behaviour of unsaturated loess is only associated with GSPM because there is no additional action caused by other phases on the soil structure. As elastic deformation happened, the other phases would adapt the space adjustment and resist this kind of change due to tensile/compressive counter-forces. The magnitude of counter-forces jointly differs with the deformation and the own strength of void structure due to GSPM. Within the period of elastic-plastic deformation, counter-forces are larger than previous elastic-period in elastic portions of soil; to the contrary, other phases can do the counteraction no longer because the arrangement of solid particles is easily altered and the shrink-swell ratio of void is relatively small in plastic portions. In the case of plastic period, the counteraction of air and gravitational water onto GSPM is going to lose completely. It is distinct that, therefore, the influence of other phases of unsaturated loess on GSPM is a kind of adaptability response caused by the space arrangement of generalized solid particles due to external loadings and only happened in the case of elastic deformation while the dynamic residual strain occurs. This analysis discloses other phases of air and gravitational water within unsaturated loess could not evidently contribute to the structure strength.

At a natural/certain stress condition, characteristics of GSPM of unsaturated loess are associated with grain properties. The properties mainly include physical shape, spatial arrangement, and interacting state among soil particles. In a brief way, the physical shape could be described by size-grade distribution; the spatial arrangement could be indicated by void ratio; and the interacting state could be figured by cohesion and internal friction angle. The interacting state, generally, which mainly contributes to the structure strength of soil mass, is jointly influenced by physical shapes and spatial arrangements of generalized solid particles. The cohesion and internal friction angle, meanwhile, are critical parameters to figure the structure strength of soil mass. Strength characteristics of GSPM of unsaturated loess, therefore, could be defined by parameters of cohesion and internal friction angle. Moreover, the dynamic residual strain of natural loess under strong seismic loadings is a kind of compressive deformation. This means the unsaturated loess has to provide an enough possibility of spatial volume compression while dynamic residual deformation occurs; otherwise, the residual strain could not be generated. Consequently, the void ratio associated with the spatial arrangement of soil particles is certainly one of critical parameters influencing the dynamic residual strain of unsaturated loess. Here, the author investigated the magnitude estimation of dynamic residual deformation applied these critical parameters of natural loess (cohesion, internal friction angle and void ratio) and other critical influence factors, i.e. features of seismic loadings (peak value and duration), and stress state of field (consolidation stress). This way adopted by authors is whether reasonable or not; the below analysis results may provide an answer.

2.2. Test data of loess samples in laboratory

The author firstly collected untrimmed samples of unsaturated loess from a typical loess field, and then acquired the data of above-mentioned critical influence parameters of soil by means of laboratory tests. Concretely, the data of cohesion and internal friction angle were obtained by static triaxial apparatus, whereas dynamic residual strain by means of dynamic triaxial test. Other data of physical properties including void ratio were expediently achieved through laboratory geotechnical tests.

Figure 2.1 shows the panoramic view of dynamic triaxial test, including the definition of dynamic residual strain. For dynamic tests adopted by authors, confining pressures are jointly calculated by dynamic stress (σ_d) and lateral-compression coefficient (K_0). In this case, loess samples are confined. Dynamic stress is experientially estimated due to the consolidation stress of each sample; and the stress axially exerts 60 times. We record one data of dynamic residual strain each 10 times; and finally there are 6 data for each untrimmed sample to describe its dynamic behaviour of residual deformation. Compression values of void ratio, meanwhile, are obtained by porous difference between before and after loaded. The all data in laboratory are summarized in Tab. 2.1 and Fig. 2.2.

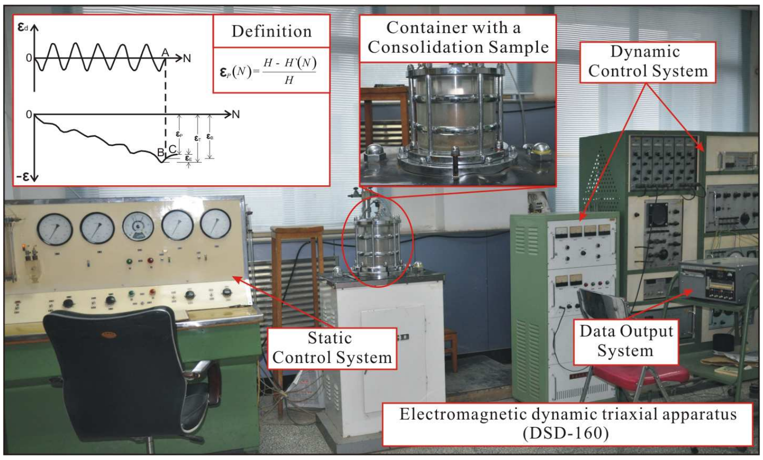
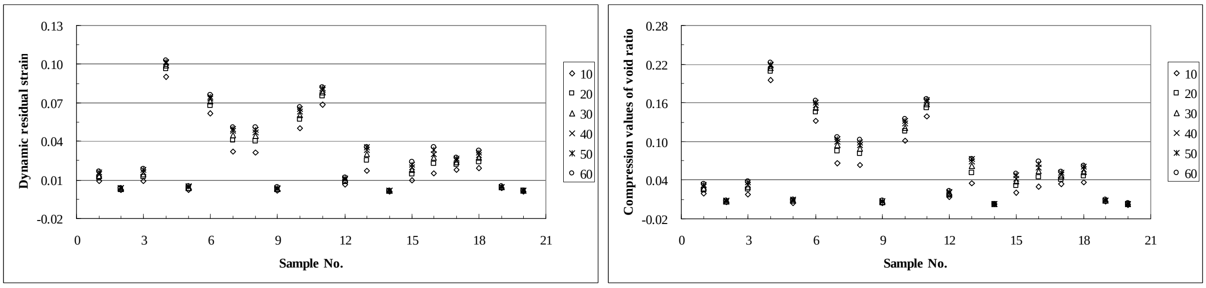


Figure 2.1. Laboratory panoramic view of dynamic triaxial test and definition of dynamic residual strain of unsaturated loess

Table 2.1. Laboratory data of untrimmed samples of unsaturated loess

Sample No.	Burial depth (m)	Unit weight (kN/m^3)	Water content (%)	Void ratio	Internal friction angle (°)	Cohesion (kPa)	Consolidation stress (kPa)	Dynamic stress (kPa)
1	4	14.3	12.1	1.073	30.7	62.6	57.2	42.1
2		14.6	10.8	1.008	32.7	114.6	58.4	31.9

3		14.4	11.9	1.055	30.7	101.0	57.6	43.2
4	8	14.0	14.7	1.166	29.6	47.1	112.1	102.3
5		15.2	15.3	1.008	29.8	67.1	121.5	36.5
6		14.2	15.1	1.143	29.5	45.2	113.7	80.7
7		14.7	16.0	1.088	29.3	40.9	117.6	56.0
8	12	14.6	14.4	1.018	29.7	48.6	175.2	69.9
9		14.9	14.1	1.018	30.5	50.7	178.8	36.8
10		14.4	15.7	1.018	29.2	42.3	172.9	85.6
11		14.3	15.0	1.018	29.5	45.7	171.7	114.2
12	16	15.0	8.0	0.971	34.7	160.7	239.9	144.5
13		14.2	10.7	1.061	31.2	72.8	227.4	98.2
14		14.7	10.9	1.000	32.6	112.8	235.2	45.9
15		13.8	10.9	1.126	33.2	53.4	221.1	68.9
16		14.9	10.0	0.971	33.2	126.0	238.3	161.4
17	20	15.1	8.0	0.901	34.7	160.5	301.8	142.8
18		15.1	8.2	0.929	34.6	157.1	301.8	185.0
19		15.1	8.1	0.916	34.6	159.2	301.8	89.8
20		15.2	8.6	0.898	34.3	150.4	303.8	43.8



(a) (b)

Figure 2.2. Laboratory data of dynamic residual strain and compression values of void ratio of untrimmed samples of unsaturated loess under different loading times

2.3. Theoretical relation

As shown in Fig. 2.3, the author adopted an ideal model with the same area (A) at the top and bottom, the height (H), and the initial void ratio (e_i) to analyze the theoretical relationship of dynamic residual strain, compression value of void ratio and initial void ratio of unsaturated loess. After a seismic loading ($g(t)$) exerted, the new area (A\`), height ($H$\`) and void ratio (e_f) of the model could be bore. Within the model, volumes of single phase of air, water and solid and total void are respectively marked by V_a, V_w, V_s and V_v.

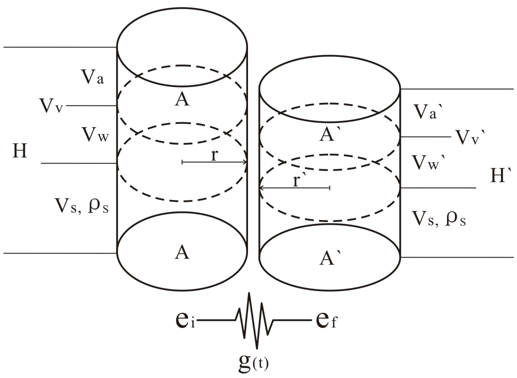


Figure 2.3. Ideal model for deformation analysis of three phases of air, water and solid of unsaturated loess

As the ideal model of unsaturated loess suffers residual strain under seismic loadings, compressive and tensile strains could respectively occur in axial and lateral directions. According to the definition of Poisson's ratio (ν), we obtain the equation

$$\nu = [(r`-r)/r]/[(H-H`)/H] \tag{2.1}$$

Based on the definition of dynamic residual strain of unsaturated loess (see Fig. 2.1), we achieve the equation

$$\varepsilon = (H-H`)/H \tag{2.2}$$

From Eqn. 2.2, Eqn. 2.1 can be written as

$$r` = (1+\nu\varepsilon)r \tag{2.3}$$

According to three phases of air, water and solid, another expression of Eqn. 2.2 is

$$\varepsilon = \{[(H_a + H_w) + H_s] - [(H_a` + H_w`) + H_s`]\}/[(H_a + H_w) + H_s] \tag{2.4}$$

where H_a, H_w and H_s are respectively the heights of three phases of air, water and solid; and $V = HA = (H_a + H_w + H_s)A$.

From Eqn. 2.3, Eqn. 2.4 can be written as

$$\varepsilon = \{[(V_a + V_w) + V_s] - (1+\nu\varepsilon)^{-2}[(V_a` + V_w`) + V_s`]\}/[(V_a + V_w) + V_s] \tag{2.5}$$

Here, we suppose the solid volume does not alter in any case of dynamic residual strain, a simple expression of Eqn. 2.5 is

$$\varepsilon = 1 - (1+\nu\varepsilon)^{-2}[(V_a` + V_w`) + V_s`]/[(V_a + V_w) + V_s] \tag{2.6}$$

The definition of void ratio before and after loading exerts is respectively $e_i = V_v / V_s$ and $e_i = V_v`/V_s$. Thus a new expression of Eqn. 2.6 is

$$\varepsilon = 1 - (1+\nu\varepsilon)^{-2}[(e_{af} + e_{wf}) + 1]/[(e_{ai} + e_{wi}) + 1] \tag{2.7}$$

where e_a and e_w are respectively void ratios of two phases of air and water; and $e = e_a + e_w$.

We suppose dynamic residual strain of unsaturated loess is only associated with the compression of void ratio and introduce a definition of compression value of void ratio ($\Delta e = e_i - e_f$; here ignored the individual void deformation of air and water due to the experiential relationship of void dynamic deformation). Eqn. 2.7 can be written as

$$\varepsilon = 1 - (1+\nu\varepsilon)^{-2}(1 - \Delta e/(e_i + 1)) \tag{2.8}$$

The simple expression of Eqn. 2.8 is

$$\nu^2\varepsilon^3 + (2\nu - \nu^2)\varepsilon^2 + (1-2\nu)\varepsilon = \Delta e/(e_i + 1) \tag{2.9}$$

At the confined condition ($\nu = 0$), Eqn. 2.9 has a simplified expression as the follow.

$$\varepsilon = \Delta e / (e_i + 1) \tag{2.10}$$

The author, here, adopt Eqn. 2.10 to describe the dynamic residual deformation of unsaturated loess under seismic loadings because the actual stress condition in field is approximately confined.

2.4. Empirical relation

Because of the complexity of dynamic residual deformation of unsaturated loess under seismic loadings, the author analyzed the relationship of compression value of void ratio, structure strength, consolidation pressure and seismic loading based on test data of loess samples in laboratory. Within this process, the concept of stress ratio (R_s) was introduced as follows due to the indistinct relation between dynamic stress and compression value of void ratio (see Fig. 2.4).

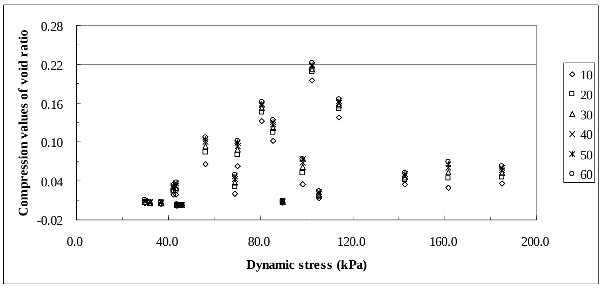


Figure 2.4. Relationship between dynamic stress and compression value of void ratio of untrimmed samples of unsaturated loess

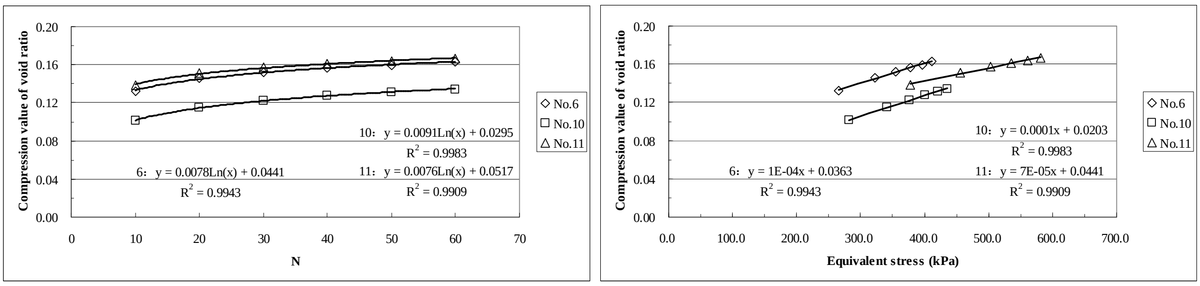
The brief expression of R_s is

$$R_s = R(f(\sigma_d)/\tau_c) = f(\sigma_d)/\tau_c \tag{2.11}$$

Considering the consolidation stress (σ_c) in the field of unsaturated loess, the Mohr-Coulomb criterion can be written as

$$\tau_c = C + \sigma_c \tan\varphi \tag{2.12}$$

As shown in Fig. 2.5, laboratory data show that compression value of void ratio gradually increases with loading times of dynamic stress for single untrimmed sample of unsaturated loess and the development feature can be perfectly described by the logarithmic function.



(a) (b)

Figure 2.5. Examples of relations between compression value of void ratio and loading times of dynamic stress (N)/equivalent stress ($f(\sigma_d)$) for single untrimmed sample of unsaturated loess

Consequently, we defined an equivalent stress ($f(\sigma_d)$) to figure the influence of loading times of dynamic stress (N) on a certain untrimmed sample of unsaturated loess as the follow.

$$f(\sigma_d) = (1 + \ln(N))\sigma_d \tag{2.13}$$

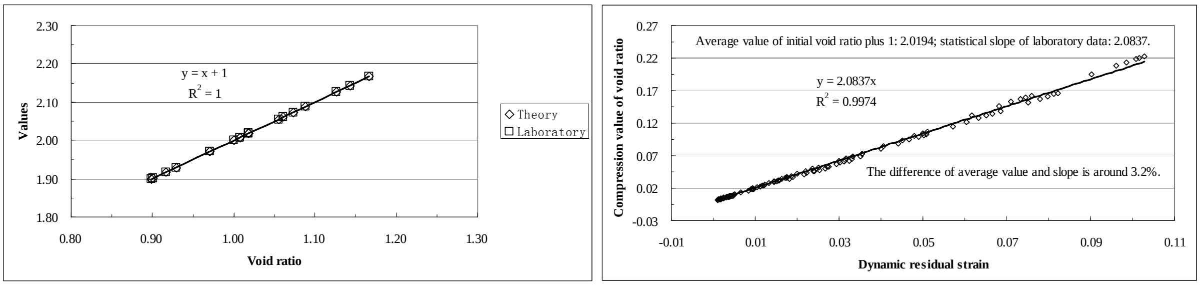
From Eqn. 2.12 and Eqn. 2.13, the detailed expression of Eqn. 2.11 is

$$R_s = [1 + \ln(N)]\sigma_d / (C + \sigma_c \tan\varphi) \tag{2.14}$$

3. RESULTS

3.1. Laboratory data for Eqn. 2.10

As one of essential relations to describe dynamic residual deformation of unsaturated loess under seismic loadings, the rationality of Eqn. 2.10 needs to be verified carefully. The analysis results based on laboratory data are shown in Fig. 3.1.

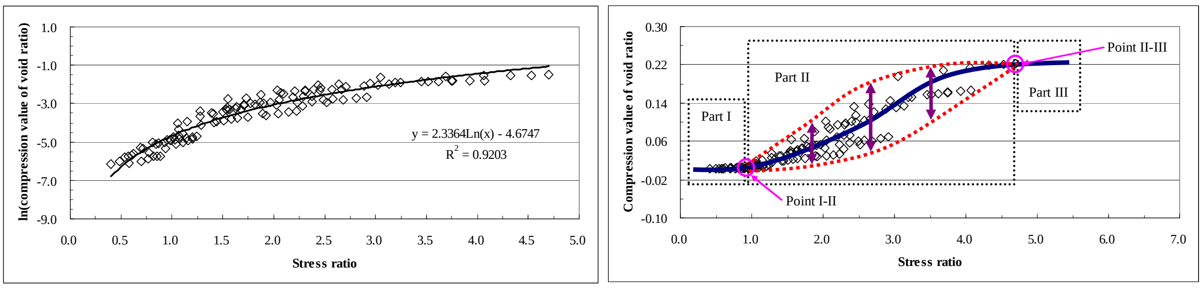


(a) (b)

Figure 3.1. Quantitative relationship of dynamic residual strain and void ratio of untrimmed samples of unsaturated loess

3.2. Empirical relationship of void dynamic deformation

Based on laboratory data in Tab. 2.1 and Fig. 2.2(b), and relation of Eqn. 2.14, we can obtain the empirical relationship of void dynamic deformation of unsaturated loess under seismic loadings. The results are shown in Fig. 3.2.



(a) (b)

Figure 3.2. Empirical relationship and essential characteristics of void dynamic deformation of untrimmed samples of unsaturated loess

Within Fig. 3.2(b), the theoretical curve of void dynamic deformation (heavy line) can be distinctly divided into three parts (Part I: before the initial dynamic stress, and with a residual strain around 0; Part II: the most complex development stage, and the discreteness maybe influenced by calculated errors of Eqn. 2.14 due to laboratory data of cohesion and internal friction angle; Part III: after the ultimate dynamic stress, and with a residual strain around a constant). Points of I-II and II-III figure the boundary between adjacent stages of void dynamic deformation of unsaturated loess.

3.3. Magnitude estimation method of dynamic residual strain of unsaturated loess

Based on Fig. 3.2(a), we can achieve an empirical relation between compression value of void ratio (Δe) and stress ratio ($f(\sigma_d)$) as the follow.

$$\ln(\Delta e) = a\ln(R_s) + b \tag{3.1}$$

The simplified expression of Eqn. 3.1 is

$$\Delta e = b\grave{}R_s^{\,a} \tag{3.2}$$

where a and b are both statistical parameters due to laboratory test data of stress ratio and compression value of void ratio, and $b\grave{} = e^b$; from Fig. 3.2(a), $a = 2.3364$ and $b = -4.6747$, and then $b\grave{} = 0.009328$.

Generally, the equivalent cyclic shear stress of seismic loadings (τ_{av}) can be calculated by means of Seed's method (Seed et al, 1971) and the formula is

$$\tau_{av} = 0.65\gamma z r_d a_{\max} / g \tag{3.3}$$

where γ, z, r_d, $a_{\max}$ and g are respectively unit weight, burial depth, reduction coefficient of depth, horizontal component of peak ground acceleration and gravity acceleration.

In the practice of laboratory triaxial test, dynamic stress (σ_d) is the double of equivalent cyclic shear stress (τ_{av}) (Qian et al, 1996), which means

$$\sigma_d = 2\tau_{av} \tag{3.4}$$

From Eqn. 2.10, Eqn. 2.14, Eqn. 3.2, Eqn. 3.3 and Eqn. 3.4, we propose a magnitude estimation method of dynamic residual strain of unsaturated loess under seismic loadings with a semi-empirical formula as the follow.

$$\varepsilon = e^b\{1.3\gamma z r_d a_{\max}[1+\ln(N)]/(C+\sigma_c \tan\varphi)/g\}^a/(e_i+1) \tag{3.5}$$

4. CONCLUSIONS

(1) As a special consolidation, dynamic residual strain of unsaturated loess is critically influenced by three aspects of soil parameters, features of seismic loadings and stress state in field. Critical influence parameters of unsaturated loess mainly include cohesion, internal friction angle and void ratio. Features of seismic loadings can be figured by peak value and duration of ground motion. The stress stated in field may be briefly described by consolidation stress.

(2) The theoretical relation of dynamic residual strain and void ratio reveals the physical deformation process, which means dynamic residual deformation of unsaturated loess under seismic loadings is distinctly caused by the compression of void volume of soil mass. Under a certain external dynamic loading, the final compressive magnitude is only associated with the under-compacted status of unsaturated loess. Therefore, an enough strong seismic loading may cause the natural loess suffered dynamic residual strain incompletely to generate residual deformations again.

(3) There is an indistinct relationship between dynamic stress and dynamic residual deformation of unsaturated loess because the residual strain has relations not only with the loading intensity, but also with the structure strength of soil mass. For any field of natural loess, physical parameters of soil are always so uncertain that test data of dynamic residual strain in laboratory is jointly influenced by external seismic loadings and inherent structure strength of soil. The inherent strength is obviously and absolutely different. Consequently, it is impossible to understand reasonable laws of dynamic residual deformation of unsaturated loess by means of the simple analysis of laboratory data of residual strain under some certain dynamic loadings. These difficulties spur the author to find out new thoughts onto the topic of dynamic residual deformation of unsaturated loess.

(4) The magnitude estimation method proposed by authors could reasonably compare the diversity of dynamic residual strain of natural loess regardless of the soil collected from any burial depth or field because its essential formulas are established based on the physical process and mechanical mechanism of plastic deformation of unsaturated loess under dynamic loadings. Although the second relation of void dynamic deformation is merely analyzed by an empirical way, the fine relevance between stress ratio and compression value of void ratio (both of new concepts introduced here) based on laboratory test data still indicate us the further direction to investigate and establish the reasonable/practical constitutive model of natural loess under external loadings.

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