Soil Dynamics and Earthquake Engineering 104 (2018) 418–431

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Earthquake-induced settlement of a clay layer

Hidemasa Sato[a,b], Tran Thanh Nhan[c,*], Hiroshi Matsuda[a]

[a] Graduate School of Sciences and Technology for Innovation, Yamaguchi University, 2-16-1 Tokiwadai, Ube, Yamaguchi 755-8611, Japan
[b] Fukken Co. Ltd., 2-10-11 Hikarimachi, Higashi-ku, Hiroshima 732-0052, Japan
[c] Hue University of Sciences, Hue University, 77 Nguyen Hue, Hue City, Vietnam

ARTICLE INFO

Keywords:
Clay
Cyclic shear
Plasticity index
Pore water pressure
Post-cyclic settlement

ABSTRACT

A model for pore water pressure accumulation and settlement of saturated clay layer induced by uniform and irregular cyclic shear strains was developed by concerning the direction of cyclic shear strain. To apply this model to any kinds of clay, the effects of Atterberg's limits of cohesive clay on the cyclic shear-induced pore water pressure and the settlement were observed by using the strain-controlled cyclic simple shear test apparatus which can control the cyclic shear direction. In conclusion, the effects of Atterberg's limits of clay on the cyclic shear-induced pore water pressure accumulation and settlement were clarified by using the cumulative shear strain. Based on the experimental results, estimation methods for the pore water pressure accumulation and post-cyclic settlement of clay with a wide range of Atterberg's limits were developed. Furthermore, to apply the proposed methods to the earthquake-induced ground motions, a transformation procedure of irregular cyclic shears to the equivalent uniform ones including the effect of cyclic shear direction was developed and the practical applicability was confirmed.

1. Introduction

It is usually well understood that the clay layer is relatively safe for the earthquake-induced liquefaction or another ground damages. The excess pore water pressure, however, may accumulate to a relatively high level [1,2] and by its dissipation, additional settlements would occur, and such a settlement has been recorded together with the damage of structures founded on clay layer after major earthquakes [3–9].

Fig. 1 shows the location of boreholes and installation depths of seismometers (in borehole BH1) and the differential settlement gauges (in borehole BH6) in the soil profile at Port-Island, *i.e.* an offshore man-made island in Kobe, Japan. The measurement of settlement was started almost three years before Hyogo-ken Nanbu earthquake which occurred on January 17, 1995 and continued for more than three years after the earthquake. The soil strata consists of an alluvial clay layer (hereinafter shown as Ma13) which is overlaid by the artificial landfill of sand and gravel materials and underlain by a series of Pleistocence layers including a sand layer (Dg1), a clay layer (Ma12) and a gravelly sand layer (Dg2) (Fig. 1b and c).

The records of landfill and ground settlement at Port-Island are shown in Fig. 2(a) and (b), respectively. In Fig. 2(b), the settlements at the ground surface and at the bottom of Ma13 layer (K.P.− 33.3 m depth) are shown by symbols and therefore, the differential settlement of these two layers can be calculated as shown by solid line (line ③). The landfilling duration was about 800 days and the induced settlement of Ma13 layer and landfill layer during this period might be due to the surcharge loading. The construction of landfill completed about 100 days before the Hyogo-ken Nanbu earthquake and because the landfill layer was constructed by coarse materials with high permeability, the observed settlement from the completion of landfill to the occurrence of the earthquake is considered mainly by the consolidation settlement of Ma13 layer under the constant surcharge loading. Based on the observed data in this period, the settlement-time relations of Ma13 layer can be predicted by the hyperbolic method and shown by the bold curve (curve I) in Fig. 2(b). Such a prediction of the settlement-time relations of Ma13 layer has been carried out by Matsuda [11]. In addition, immediately after the Hyogo-ken Nanbu earthquake, the ground surface settled about 26.4 cm and this settlement is very close to those of Ma13 layer and the artificial fill (line ③). This means that the earthquake-induced instantaneous settlement is mainly generated by the liquefaction of the landfill layer. Since the surcharge loading was kept constant and if the earthquake would not occur, the consolidation of Ma13 layer would follow the predicted curve I and due to the liquefaction-induced settlement of the landfill, the curve I might move to the position of the dotted line (curve II).

The coefficient of consolidation of Ma13 layer was determined as c_v = 100 cm^2/day [12] and this clayey layer was improved by using the sand drain method. Therefore, the settlement-time relations of Ma13

* Corresponding author.
E-mail addresses: nhan_hueuni@yahoo.com, nhan.hueuni@gmail.com (T.T. Nhan).

https://doi.org/10.1016/j.soildyn.2017.11.006
Received 5 May 2017; Received in revised form 23 August 2017; Accepted 4 November 2017
0267-7261/

Nomenclature

A	experimental constant
α	experimental parameter
B	experimental constant
β	experimental parameter
C	experimental constant
C_c	compression index
C_{dyn}	cyclic recompression index induced by cyclic loading
c_v	coefficient of consolidation
e_0	initial void ratio
EW	East - West direction
ε_V	post-cyclic settlement in strain
f	frequency of cyclic shear strain
F	experimental constant
G	experimental constant
G_{ma}	shear modulus
G^*	cumulative shear strain (induced by uniform cyclic shear)
G_i^*	irregular cumulative shear strain (induced by irregular cyclic shear)
G_u^*	equivalent uniform cumulative shear strain
G_s	specific gravity
γ	shear strain amplitude
γ_{dyn}	equivalent uniform shear strain amplitude
γ_{EW}	irregular shear strain amplitude in *EW* direction
γ_{max}	maximum amplitude of irregular multi-directional cyclic shear strain
γ_{maxEW}	maximum irregular shear strain amplitude in *EW* direction
γ_{maxNS}	maximum irregular shear strain amplitude in *NS* direction
γ_{NS}	irregular shear strain amplitude in *NS* direction
γ_{sat}	saturated unit weight
γ_t	wet unit weight
γ_x	uniform shear strain amplitude in *X* direction
γ_y	uniform shear strain amplitude in *Y* direction
h_0	initial height of specimen or clay layer
I_p	plasticity index
φ_f	friction angle
K.P.	Kobe Port datum level
m	experimental constant
n	number of cycles
N_{cy}	equivalent effective number of cycles
N_{cyA}	equivalent effective number of cycles calculated by using the absolute definition
N_{cyR}	equivalent effective number of cycles calculated by using the relative definition
NS	North - South direction
θ	phase difference
SRR	stress reduction ratio
S	Calculated settlement of Ma13 clay layer at Port-Island after Hyogo-ken Nanbu earthquake induced by the dissipation of earthquake-induced pore water pressure
σ_{ma}	mean effective stress
σ_{v0}	initial vertical stress
σ'_{v0}	initial vertical effective stress
T	period of cyclic shear strain
Tn	total number of cycles in the acceleration record
U	degree of consolidation
U_{dyn}	pore water pressure induced by cyclic loading
U_{dyn}/σ'_{v0}	pore water pressure ratio induced by cyclic loading
u_i	amplitude of *i*-th half-cycle in the acceleration record
u_{max}	maximum amplitude of all half-cycles in the acceleration record
V_s	velocity of S-wave
w_L	liquid limit
w_p	plastic limit
Δe	change of void ratio
ΔG^*	increment of cumulative shear strain induced by uniform cyclic shear
ΔG_i^*	increment of irregular cumulative shear strain
$\Delta\gamma_{EW}$	increment of irregular shear strain in *EW* direction
$\Delta\gamma_{NS}$	increment of irregular shear strain in *NS* direction
$\Delta\gamma_x$	increment of uniform shear strain in *X* direction
$\Delta\gamma_y$	increment of uniform shear strain in *Y* direction
Δh	settlement of specimen or clay layer
$\Delta\sigma'_v$	decrease of vertical effective stress
$\lvert\Delta\sigma'_v/\sigma'_{v0}\rvert$	effective stress reduction ratio
ΔS	Final settlement of Ma13 clay layer at Port-Island after Hyogo-ken Nanbu earthquake induced by the dissipation of earthquake-induced pore water pressure and by the secondary consolidation
$\Delta S_{90\%}$	Settlement of Ma13 clay layer at Port-Island after Hyogo-ken Nanbu earthquake induced by the dissipation of earthquake-induced pore water pressure

layer can be calculated by Barron's method [13], which was proposed for the consolidation under the drainage in the horizontal direction such as those improved by sand drain method. Results show that the degree of consolidation at the Ma13 clayey layer reaches U = 90% at 260 days after the earthquake and the differences between the predicted curve (curve II) and the observed line (line ③) were determined as $\Delta S_{90\%}$ = 10.3 cm (Fig. 2b). Since the surcharge load-induced settlement of Ma13 layer before the earthquake has been included in curve II and therefore, $\Delta S_{90\%}$ = 10.3 cm involves only the earthquake-induced settlement of Ma13 layer due to the dissipation of the pore water pressure generated by the earthquake. In addition, the differences between curve II and the line ③ becomes almost constant as ΔS = 17.0 cm after 600 days from the occurrence of the earthquake (Fig. 2b).

In this study, normally consolidated specimens of Kaolinite clay, Tokyo bay clay and Kitakyushu clay with a wide range of Atterberg's limits were subjected to uniform and irregular cyclic shears by using the multi-directional cyclic simple shear test apparatus. The effects of the cyclic shear direction and the Atterberg's limits of clayey soils on the pore water pressure accumulation and the post-cyclic settlement were observed. An estimation method of the earthquake-induced pore water pressure and the post-earthquake settlement due to the dissipation of the pore water pressure were newly developed and its practical applicability was then confirmed.

2. Experimental aspects

2.1. Multi-directional cyclic simple shear test apparatus

Fig. 3(a) and (b) show the outline and the photo of the multi-directional cyclic simple shear test apparatus, in which the situation of specimen in the Kjellman type shear box is also shown. By using the electro-hydraulic servo system, any kinds of cyclic simple shear deformation can be applied to the specimen independently from two orthogonal directions. For the vertical load, on the top surface of specimen, a predetermined vertical stress can be applied by using the aero-servo system. The specimen is confined in a rubber membrane surrounded by a stack of 15, 18 and 21 acrylic rings for the case of Kaolin, Tokyo bay clay and Kitakyushu clay, respectively. Each acrylic ring has the dimensions of 75.4 mm in inside diameter and 2 mm in thickness (Fig. 3b). Under such a condition, the specimen is prevented from the radial expansion during the test, while the shear deformations are allowed.