An Attempt to Replicate the So-Called "Trampoline Effect" in Computational Geomechanics

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15 WCEE
LISBOA 2012

SUMMARY
In this research, we reproduced the vertical asymmetrical acceleration response observed at the ground surface at KiK-net measurement station IWTH25 (West Ichinoseki) during the 2008 Iwate-Miyagi earthquake using the finite deformation analysis code ***GEOASIA***, which employs an elasto-plastic constitutive equation, the SYS Cam-clay model, that incorporates the concept of soil skeleton structure. Also, it was found that the asymmetrical acceleration motions in the vertical direction measured at the ground surface at this location can be caused by a ground uplift phenomenon associated with loosening of heavily overconsolidated soils.

Keywords: Trampoline effect, Stronseismic motion, Elasto-plastic analysis, Loosening, ground uplift

1. INTRODUCTION

In the 2008 Iwate-Miyagi earthquake, strong seismic motions (three-component synthesis: 4022 gal) were recorded on the ground surface at KiK-net measurement station IWTH25 (West Ichinoseki), which was closest to the epicenter. Aoi et al. (2008) pointed out that the vertical acceleration response at the measurement station was extremely asymmetric, with the upward acceleration more than double that of the downward acceleration. Symmetrical vertical motions were recorded underground at that measurement station, so the asymmetry was clearly generated in the transmission path to the ground surface. Aoi et al. (2008) stated that the phenomenon in which an asymmetric response is produced even though a vertically symmetrical seismic motion was input cannot be explained by nonlinear wave motion theory known at present, let alone elastic wave motion theory. Therefore, they propose that the vertically asymmetric pulsating waveform is produced by the medium failing and cracks extending so that the medium partially has the properties of a granular medium. They refer to the measured asymmetric acceleration response in the vertical direction as the trampoline effect based on its resemblance to the acceleration motions of a body on a trampoline.

In this paper, we attempt to reproduce the asymmetrical acceleration response in the vertical direction using nonlinear elasto-plastic geomechanics based on continuum mechanics. This paper utilizes an elasto-plastic constitutive equation, the SYS Cam-clay model (Asaoka et al., 2002), as the soil skeleton constitutive equation. This constitutive equation is an elasto-plastic constitutive equation obtained by incorporating the concept of skeleton structure into the Cam-clay model (Roscoe, 1958), which was developed for clay in the normally consolidated condition produced by remolding in the laboratory. This constitutive equation was produced with the aim of describing the various mechanical behaviors of soils, including naturally deposited clay, sand, intermediate soils, etc. The same soil can reproduce the mechanical behavior of soil in various states with one set of material constants. Also, to solve the boundary value problem, the soil-water coupled finite deformation analysis code ***GEOASIA***, which employs the SYS Cam-clay model, was used. ***GEOASIA*** is a code that integrates the rate-type equations of motion, after finite element discretization, with time to obtain the motion of soil. It is capable of calculation without distinguishing between quasi-static phenomena in which acceleration can be ignored and dynamic phenomena having significant accelerations.

In the following, first the volumetric change phenomena (compaction and loosening) in the soil produced by the vibrations are reproduced using the SYS Cam-clay model. These phenomena are first reproduced at the constitutive equation level to determine the volumetric expansion phenomenon (loosening) of soil due to vibration, which is the key to the mechanism for producing the asymmetric vertical acceleration response. Next, we attempt to reproduce the asymmetric vertical acceleration response using ***GEOASIA*** and at the same time identify the mechanism that is producing this response.

2. COMPACTION AND LOOSENING OF SOILS

If loosely deposited sand is placed in a container and vibrated, it will compact. This volumetric compaction phenomenon of soil due to vibration is referred to as compaction. On the other hand, if well-compacted soil is subjected to repeated shearing with a large stress amplitude, the soil will gradually crumble and expand. The volumetric expansion phenomenon due to this type of repeated shearing is referred to as loosening. It will be shown that the SYS Cam-clay model is capable of reproducing compaction and loosening. The first to be shown is compaction. Calculation was carried out using the material constants shown in Table 1 and the initial values shown in Table 2. The initial

Table 1. Material constants

Elasto-plastic parameters	
Compression index $\tilde{\lambda}$	0.180
Swelling index $\tilde{\kappa}$	0.00032
Critical state constant M	0.5
Specific volume at $q = 0$ and $p' = 98.1$ kPa on NCL N	2.300
Poisson's ratio ν	0.30
Evolution rule parameters	
Degradation index of structure a ($b = c = 1.0$)	1.5
Degradation index of overconsolidation m	100.0
Evolution index of rotational hardening b_r	0.001
Limit of rotational hardening m_b	0.7
Density of soil particles ρ_s (t/m^3)	2.650

Table 2. Initial conditions

Vertical effective stress σ_{v0}' (kPa)	294
Degree of structure $1/R_0$ *	10.0
Overconsolidation ratio $1/R_0$	1.0
Degree of anisotropy ζ_0	0.00
Lateral pressure coefficient K_0	0.90

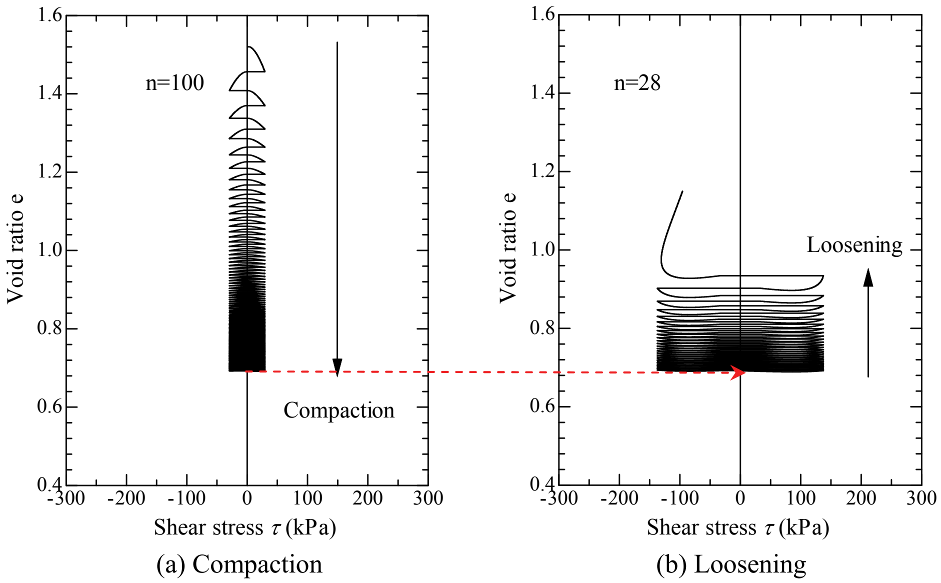


Figure 1. Compaction and loosening of soil

values were given assuming soil in a loose state with developed structure. Fig. 1(a) shows the relationship between the void ratio (e) and the shear stress (τ) when simple shear with a small amplitude is applied to the soil. When simple shear is applied, the stress in the vertical direction is constant. Fig. 1(a) reproduces the situation where the soil compacts greatly due to the initial vibration and then gradually becomes more difficult to compact. During this time, the soil structure decays, the heavily overconsolidation ratio gradually accumulates, and finally the soil is in an heavily overconsolidated state with low-level structure. Next, loosening is reproduced. Fig. 2(b) shows the behavior when soil that is compacted as described above is subjected to repeated shearing with a stress amplitude larger than when it was compacted. In contrast to Fig. 1(a), the soil initially starts to loosen, and finally a sudden swelling state is reproduced. During this time, the initially heavily overconsolidated soil gradually becomes a normally consolidated soil. In this way, the SYS Cam-clay model is capable of describing, with one set of material constants, the contrasting volumetric change phenomena of compaction and loosening due to repeated shearing.

3. ANALYSIS TO REPRODUCE THE VERTICAL ASYMMETRIC ACCELERATION RESPONSE

Next, the soil-water coupled finite deformation analysis code ***GEOASIA***, which employs the soil skeleton elasto-plastic constitutive equation SYS Cam-clay model, is used in an attempt to reproduce the asymmetric vertical acceleration response and the corresponding uplift of the ground surface to explain the mechanisms for producing this response.

3.1. Analysis conditions

The finite element mesh and boundary conditions used in the analysis are shown in Fig. 2. The object analyzed was a surface soil 15 m thick. The material constants were given the same values as those shown in Table 1, and the initial values were as shown in Table 3, assuming soil that is well compacted. A coupled analysis with water was not carried out as it was assumed that the ground was in a dry state. The initial stress states and the overconsolidation ratio were obtained by calculation using the self-weight and the other initial values shown in Table 3. The initial overconsolidation ratio obtained by calculation is shown in Fig. 3. It can be seen that the ground that is the subject of the analysis is in the overconsolidated state. A one-dimensional mesh was used, and the side surfaces were given periodic boundaries, assuming that horizontally stratified ground moves uniformly in the

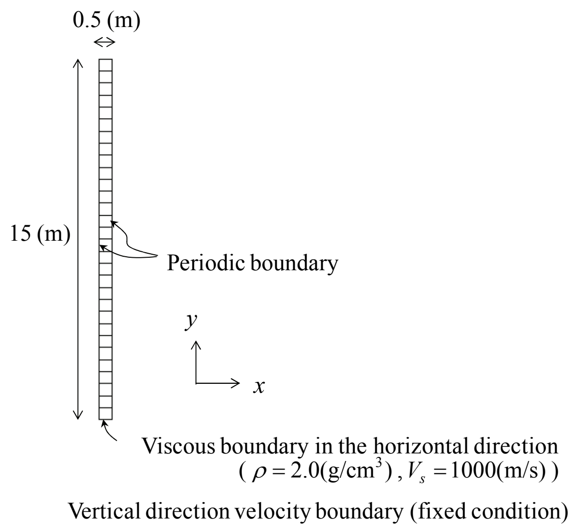


Figure 2. Finite element mesh and boundary conditions

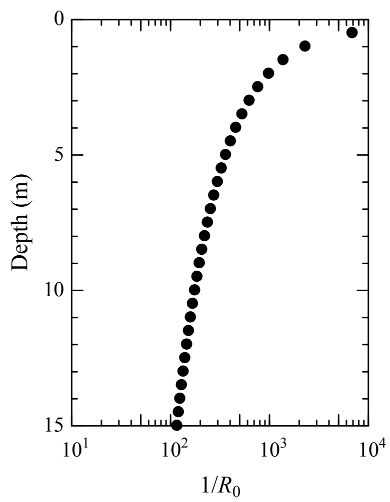


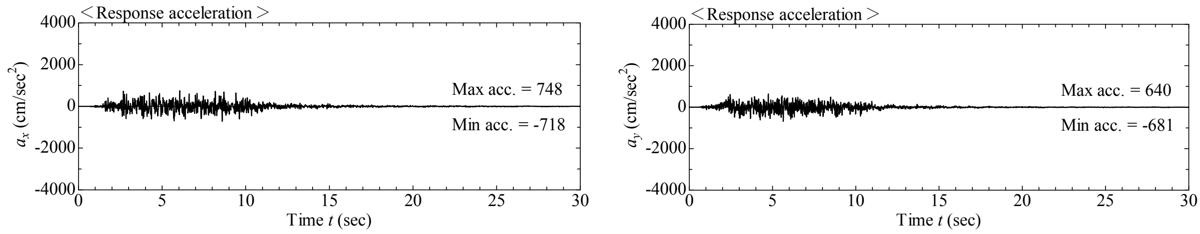
Figure 3. Distribution of the initial overconsolidation ratio with depth

horizontal direction. Also, the bottom surface was given a viscous boundary in the horizontal direction, with the density being $\rho = 2.0$ g/cm^3 and Vs = 1000 m/sec given as the material properties of the viscous boundary. In the actual ground, there was also input in the vertical direction, but in this research, displacement in the vertical direction was fixed on the bottom surface, so vertical motions were not input.

Table 3. Initial conditions

Specific volume v_0	1.4
Degree of structure $1/R_0{}^*$	1.0
Degree of anisotropy ζ_0	0.55
Lateral pressure coefficient K_0	0.60

Fig. 4 shows the seismic wave measured 260 m below ground at KiK-net measurement station IWTH25 (West Ichinoseki). This waveform is virtually symmetric in all directions, north-south, east-west, and vertical. Of these, the acceleration in the east-west direction was input to the viscous boundary of the bottom surface in the analysis.

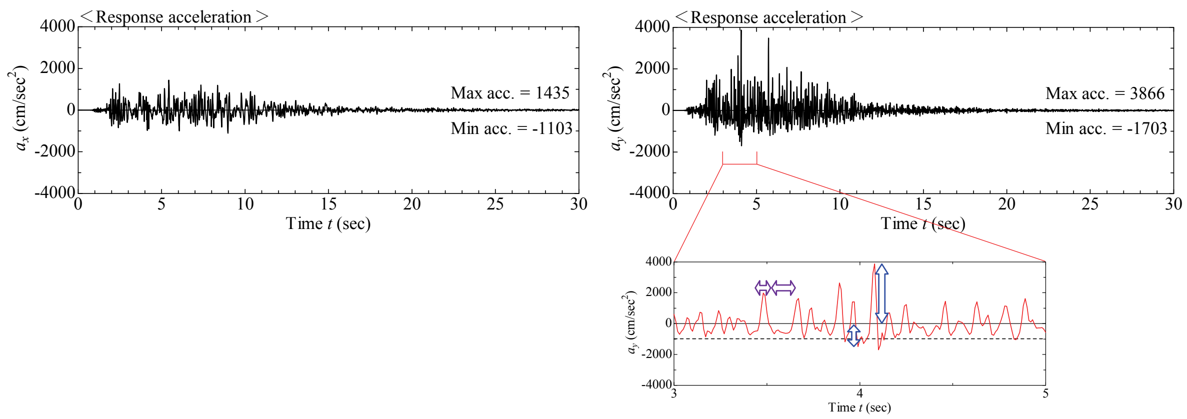


(a) Horizontal direction (East-West) (b) Vertical direction (Up-Down)

Figure 4. Acceleration record measured 260 m below ground at KiK-net measurement station IWTH25 (West Ichinoseki)

3.2. Analysis results

Fig. 5 shows the measured ground surface acceleration response at KiK-net measurement station IWTH25 (West Ichinoseki). First, the characteristics that can be seen in this figure are explained based on Aoi et al. (2008). The biggest characteristic is the asymmetry that can be seen in the

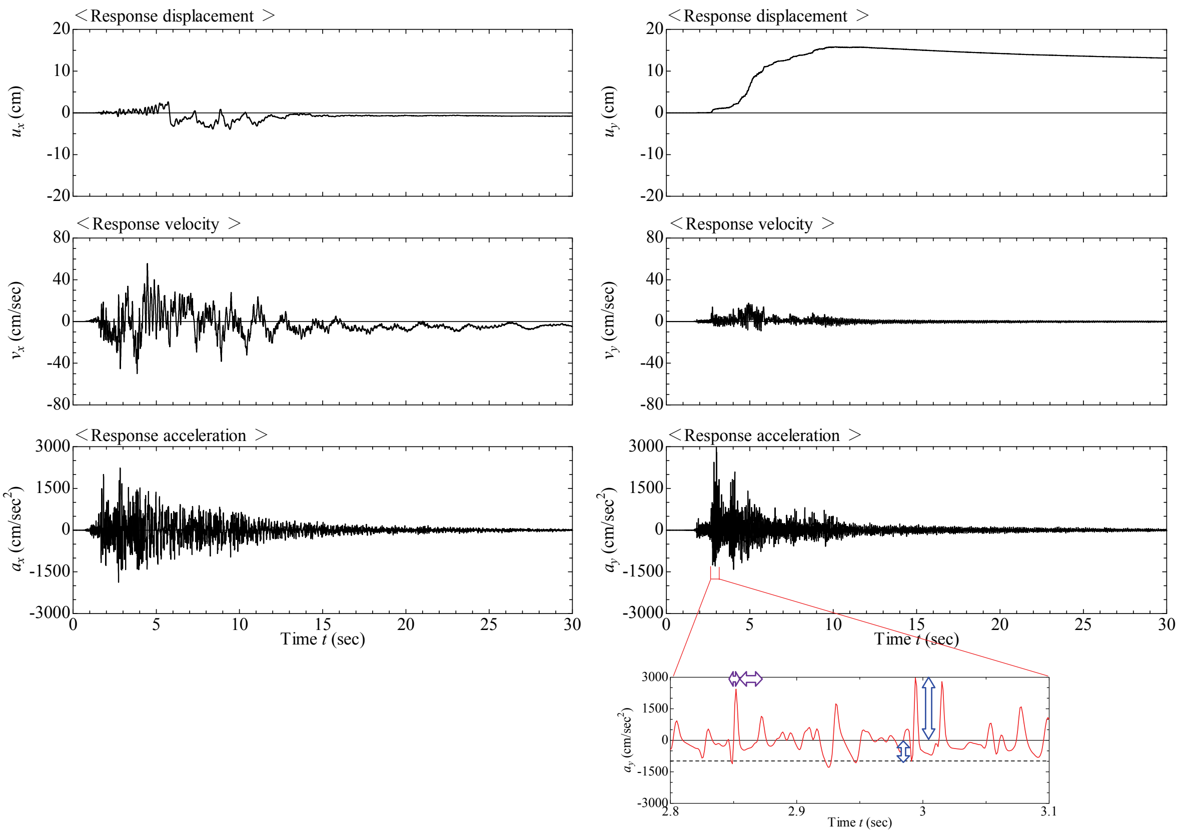


(a) Horizontal direction (East-West) (b) Vertical direction (Up-Down)

Figure 5. Acceleration record measured at the ground surface at KiK-net measurement station IWTH25 (West Ichinoseki)

acceleration time history in the vertical direction. The accelerations in the upward direction are clearly larger than the accelerations in the downward direction. From the enlarged diagram of the vertical motion, it can be seen that the acceleration in the downward direction peaks at about 1 g. In contrast to the waveform in the upward direction, which is sharply pointed, the waveform in the downward direction is pressed into a broad shape, so the waveform in the upward direction and the waveform in the downward direction are asymmetrical. Also, the values of the acceleration in the vertical direction are larger than the accelerations in the horizontal direction. In contrast, the waveform measured 260 m below ground at the same point as shown in Fig. 4 does not have this characteristic, so it can be seen that this characteristic is produced in the transmission path up to the ground surface.

Next, the ***GEOASIA*** analysis results are described. Fig. 6 shows the displacement, velocity, and acceleration time histories in the horizontal direction and the vertical direction at the ground surface. The motions in the horizontal direction are the relative motions with respect to the bottom surface of the ground. It can be immediately seen from Fig. 6 that there is clear asymmetry in the vertical acceleration response. From the enlarged diagram of the acceleration response in the vertical direction, it can be seen that there is asymmetry between the waveform in the upward direction and the waveform in the downward direction, the same as was seen in the measured results. Also, the values of acceleration in the vertical direction are larger than the accelerations in the horizontal direction. It can be seen that it is possible to reproduce the characteristic acceleration response measured at the ground surface at KiK-net measurement station IWTH25 (West Ichinoseki) using nonlinear analysis based on finite deformation theory that takes into consideration the appropriate modeling of the soil behavior and inertial forces. What is particularly noteworthy in this analysis is that the acceleration motions in the vertical direction are greater than in the horizontal direction and that this has been produced without input in the vertical direction. This is in contrast to the trampoline effect model by Aoi et al. (2008), which requires input in the vertical direction but does not require input in the horizontal direction.



(a) Horizontal direction (East-West) (b) Vertical direction (Up-Down)

Figure 6. Ground surface response (analysis results)

Next, the mechanism by which this asymmetric motion in the vertical direction is produced is considered. Fig. 7 shows a contour diagram of the change in void ratio during the earthquake. For ease of viewing, the horizontal displacements in this contour diagram are enlarged by a factor of 50, and the vertical displacements are enlarged by a factor of 2. From Fig. 7, it can be seen that the swelling of the ground increases closer to the ground surface. In the vertical displacements in Fig. 6 also, it can be seen that there is uplift of the ground surface at around 2.5 seconds. Fig. 8 shows the behavior of elements at a position about 75 cm below ground. It can be seen that as a result of the strong seismic motions in the horizontal direction, repeated shearing with a large stress amplitude is applied and loosening occurs. Fig. 9 shows the displacement, velocity, and acceleration time histories in the horizontal and vertical directions at mid-depth in the analysis area. Focusing on the acceleration time history in the vertical direction, it can be seen that virtually symmetrical acceleration motions are produced. From the displacements in the vertical direction, it can be seen that at this depth, almost no displacement in the vertical direction has been produced. From the contour diagram of the change in void ratio shown in Fig. 7, it can be seen that the amount of swelling at positions deeper than the

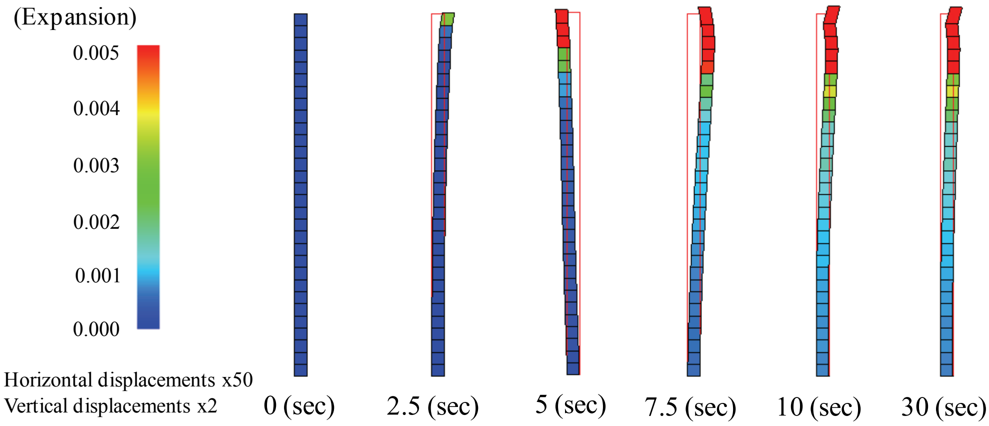


Figure 7. Change in distribution of void ratio with time

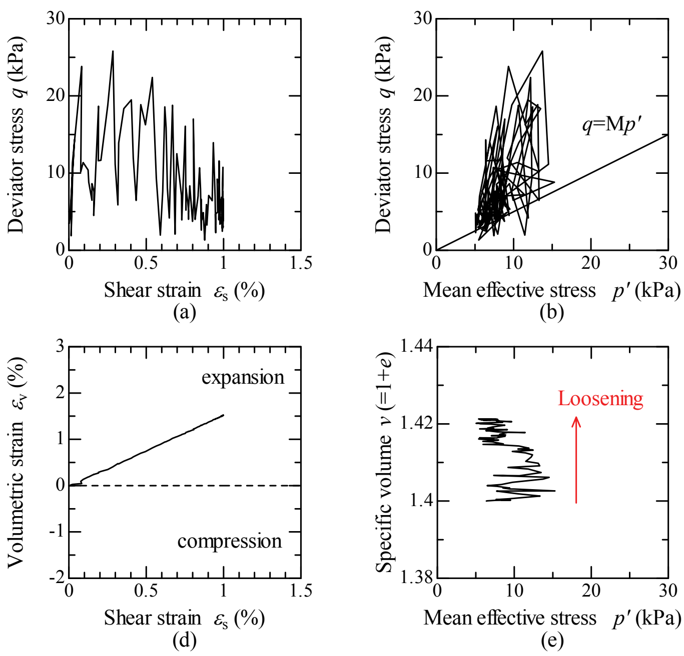
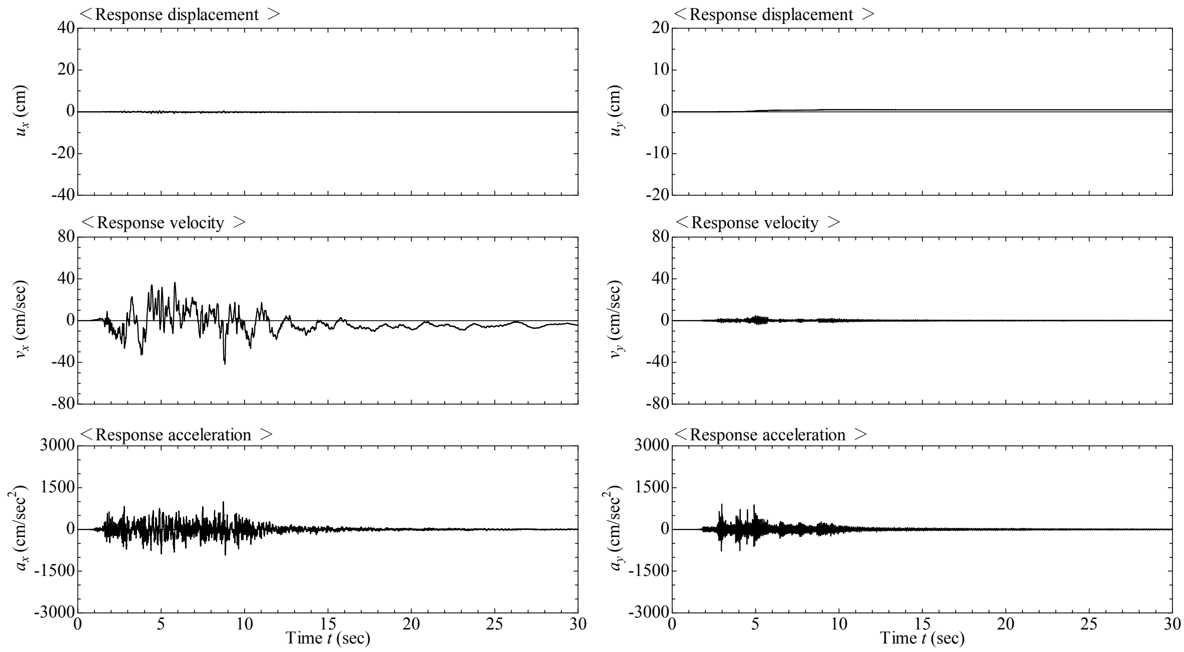


Figure 8. Element behavior near the ground surface

center of the soil column is small. In other words, the fact that asymmetry is not seen in the waveform in the vertical direction in the center of the analysis area indicates that the asymmetrical acceleration motions in the vertical direction at the ground surface were produced by uplift of the ground associated with loosening.



(a) Horizontal direction (East-West) (b) Vertical direction (Up-Down)

Figure 9. Response underground

4. CONCLUSIONS

In this research, we attempted to reproduce the asymmetrical vertical acceleration response measured at the ground surface at KiK-net measurement station IWTH25 (West Ichinoseki) during the 2008 Iwate-Miyagi earthquake using the finite deformation analysis code ***GEOASIA***, which includes an elasto-plastic constitutive equation, the SYS Cam-clay model, that incorporates the concept of soil skeleton structure. The results showed that even though acceleration was only input in the horizontal direction at the bottom surface of the ground, a vertical acceleration response was produced at the ground surface that was greater than that in the horizontal direction. Moreover, this acceleration response had the same characteristic of asymmetrical acceleration response as that measured on site. Also, it was shown that this asymmetrical vertical acceleration response can be produced by the phenomenon of uplift of the ground associated with loosening of heavily overconsolidated soil.

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