# DYNAMIC STABILITY OF A SLOPE SUBJECTED TO SURFACE WAVES AND POSSIBLE MECHANICAL ROLE OF GROUND ANCHORS

Koji UENISHI[1]*

[1]Research Center for Urban Safety and Security, Kobe University (1-1 Rokko-dai, Nada, Kobe 657-8501 Japan)
*E-mail: uenishi@kobe-u.ac.jp

Seismically-induced open cracks have been found in the top surfaces of slopes in Japan as well as in California, but the generation mechanism of such cracks has not been fully clarified yet. Recently, it has been shown that the effect of surface wave propagation on dynamic slope stability may not be negligible and Rayleigh surface waves may play a more crucial part, rather than body waves, in generating the open cracks. This paper briefly shows results of two-dimensional elastodynamic analyses of Rayleigh wave interaction with a simplified slope, with possible positions of ground anchors for preventing dynamic slope failures taken into account. Surface waves may be generated also by nearby blasting: The results may be of importance in understanding the dynamic stability of a slope in general.

***Key Words :*** *Rayleigh wave, ground anchor, dynamic stability, wave interaction, slope failure*

## 1. Introduction

A slope is one of the typical structures that may be subjected to dynamic deformation (and possibly mechanical destabilization) by seismic waves. For instance, the fill slopes in Sendai City, Japan, were subjected to dynamic loading of the 1978 Miyagi-ken-oki earthquake [Japan Meteorological Agency (JMA) Magnitude $M_j$ = 7.4], and at the top of the slopes crack openings were found. Cracks were generated at positions some 6 meters away from the corner of the slope, whose inclination was some 75 degrees. No other damage, however, was observed in the face of the slope, except for the collapse of wet masonry retaining walls at some places (Fig.1). No clear circular slip surface was recognized at the site.

The existence of open cracks at this relatively short distance from the crest in soil conditions suggests that the crest of slope was subjected to dynamic tensile stresses and the wavelength of incident seismic wave was comparable to the scale of the slope, i.e., waves in a relatively high frequency range impinged upon and interacted with the slope. In this Sendai case, considering the epicentral distance of more than 100 km, it may be more appropriate to assume that the damage was induced by surface waves, especially Rayleigh waves, because their attenuation from the source ($\sim 1/r^{1/2}$) is less than that of body waves ($\sim 1/r$) and they may acquire an increasing preponderance at a great distance $r$ from the source. Hence, in order to systematically investigate the generation mechanism of this slope failure, in the previous study[1)], dynamic interaction of a Rayleigh surface wave with a simple, wedge-shaped slope has been considered. A two-dimensional elastodynamic analysis has suggested that the amplitudes and phase shifts of the surface waves reflected and transmitted at the crest strongly depend on the inclination of the slope face, and the superimposition of the reflected and incident waves may induce large stress amplification and thus produce open cracks in the top surface of the slope.

In this contribution, the study is extended further. First, the analytical results obtained in the earlier study[1)] are summarized and the importance of the surface wave model considered here is addressed. Then, the moving particle semi-implicit (MPS) method is applied to this dynamic problem in geomechanics and full numerical

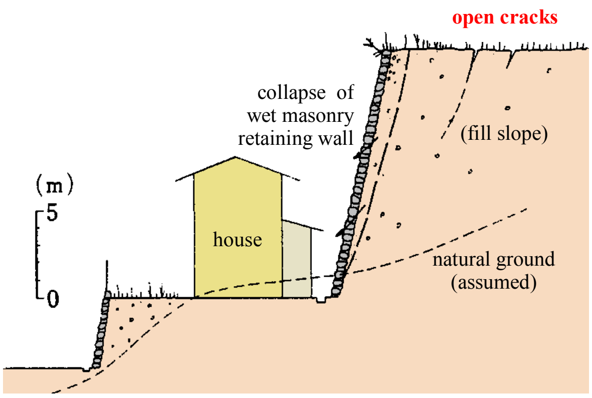



Fig.1 Typical failure of a fill slope found in Sendai, Japan, on the occasion of the 1978 Miyagi-ken-oki earthquake (modified after OYO[2]).

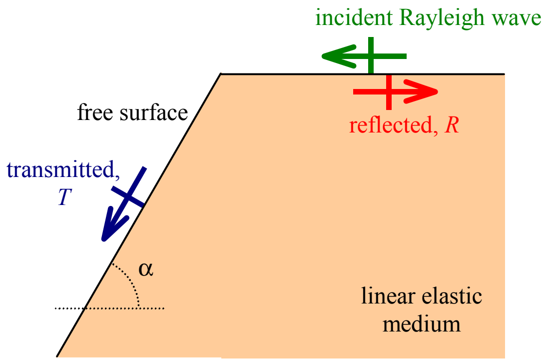



Fig.2 The slope model employed in the analysis.

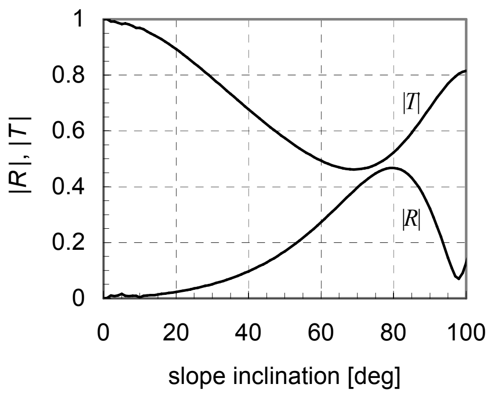



Fig.3 The effect of the slope inclination α on the reflection and transmission coefficients, |R| and |T|, respectively, for Poisson's ratio 0.25.

simulations using the MPS method are performed for the Rayleigh wave (pulse) interaction with a geometrically more complex, two-dimensional linear elastic slope. A possibly new mechanical role of reinforcing measures such as installation of ground anchors is briefly mentioned. Slope protection against surface waves may be a new but non-unimportant research subject.

## 2. Analytical Basis

As a first step toward further understanding, the reflection and transmission of two-dimensional harmonic Rayleigh waves at the corner (crest) of a simple, wedge-shaped slope (Fig.2) has been quantitatively analyzed based on the method of Fourier transformations[1]. The reflection and transmission coefficients, $R$ and $T$, defined as the ratios of the complex displacement amplitudes of the reflected and transmitted Rayleigh waves to that of the incident wave, respectively, may be semi-analytically calculated and an example is shown in Fig.3 for the case Poisson's ratio 0.25. Note that the coefficients $R$ and $T$ depend only on the slope inclination $\alpha$ and Poisson's ratio $\nu$, and they are independent of the length (frequency) of the Rayleigh wave, any other material and geometrical properties of the medium.

In Fig.3, the horizontal axis denotes the slope inclination while the vertical one corresponds to the reflection and transmission coefficients, $|R|$ and $|T|$, respectively. The figure shows the reflection coefficient $|R|$ reaches its maximum value near $\alpha = 80°$ where the amplitude of the reflected wave is approximately half of that of the incident wave (0.47 at $\alpha = 80°$). In this harmonic analysis, displacement ratios are equal to the ratios of particle velocities or accelerations, and the induced normal (tensile) stress parallel to the surface is proportional to the particle velocity (more precisely, the latter is valid in a harmonic Rayleigh wave on the free surface of a two-dimensional linear elastic half space[3]). Below 80° the reflection coefficient varies nearly monotonically and it is 0 at $\alpha = 0°$ (no reflection on the flat surface). It should be noted that near $\alpha = 100°$ (i.e., an overhang), $|R|$ is at its local minimum (0.07 at $\alpha = 98°$), suggesting that theoretically the top surface of an overhang is more reflection-resistant than the slopes with an acute inclination angle over 35°.

Figure 3 also shows the variation of the transmission coefficient $|T|$ with the slope inclination $\alpha$. Around $\alpha = 70°$, $|T|$ reaches its minimum value (0.46 at $\alpha = 69°$) and the slope face itself is subjected to a Rayleigh wave whose amplitude is less than half of that of the incident wave. It should be pointed out that at these angles (slope inclination 70-80°) in the top surface of the slope the superimposed wave amplitude (of particle displacement, velocity, acceleration, or tensile stress parallel to the free surface) is about 1.5 times the incident one, i.e., three times as large as the transmitted one, and the top surface of the slope is more likely to be subjected to open cracks than the slope face, as has been observed in Fig.1. Using this Fig.3, the possible position of crack opening in the top surface of the slope due to superimposition of the in-phase incident and reflected waves may be quantitatively evaluated[1]. For the Sendai case, Fig.3 indicates that the inclination of the slope face 75° is not particularly suitable for linear elastic slopes subjected to Rayleigh waves: More energy is reflected and therefore the superimposition of the incident and strongly reflected Rayleigh waves may result in large tensile stress to be induced near the slope crest and cracks may be initiated. Further analysis suggests that the incident Rayleigh wave frequency was about 10 Hz. In other words, if the Rayleigh waves have caused that failure, then these surface waves should contain relatively high frequencies in order to generate this type of damage. If the slope were less steep, say, if the inclination were 60 degrees, then the reflected amplitude would be reduced by 40 % and the total surface wave energy would be reduced by 26 %, and hence less damage to the top surface of the slope would be expected.

The model considered here is totally different from other so-called "realistic" models that usually assume a slope consisting of some deformable materials on top of a rigid (or energy-absorbing) bottom which is subjected to a uniform, prescribed horizontal disturbance (plane *SH* or *SV* wave incidence). For example, motivated in part by the observations of dynamic failure patterns in California, the topographic effects on the seismic response of steep cliffs subjected to vertically propagating shear waves[4)-5)] and the influence of inclined plane shear wave incidence on a steep coastal bluff[6] have been numerically analyzed: From the photographic observations of the 1906 and 1957 San Francisco earthquakes, it has been reported[5] that the vertical or nearly vertical slopes (cliffs) in the weakly cemented sands immediately south of San Francisco primarily fail by separation of a narrow block of soil along the essentially vertical tension crack at the top of the cliff and subsequent shearing of material at the base of the block. This failure is similar to that found in Sendai, but the slopes (cliffs) in California are much larger in scale, typically up to 50 m high. It has been also reported[6] that tension cracks extending 1 to 6 m behind the crests of coastal bluffs were generated by the 1989 Loma Prieta earthquake. For the observed phenomena, for instance, a time-domain analysis of the mechanical behavior of bluffs at Seacliff State Beach in California has been conducted, taking into account the propagation direction of the incident plane shear wave and site effects[6]. However, in the series of the studies, more attention was paid to the expected accelerations at the crest, and it does not seem that concrete quantitative information about the precise cause (and possible positions) of open cracks has been given. Also, it has been demonstrated[7], Rayleigh waves are strongly produced by incident *SV* waves in the neighborhood of a cliff. In order to explain the generation of open crack in the top surface at such a short distance from the crest, therefore, it might be more plausible to assume the incidence of Rayleigh surface waves of relatively high frequencies than simulating the propagation of plane body waves. However, it should be mentioned at the same time that the possible existence of Rayleigh waves in the high frequency range will not negate the strong effects of (high- and low-frequency) horizontal shear waves on structural stabilities and failures[1].

## 3. Dynamic Stress Induced in a Slope and a Mechanical Role of Ground Anchors

So far, the effect of the height and concave shape of a slope as well as dynamic transient stress development in the slope has not been included in our simplified slope model. In order to quantitatively evaluate this effect, basic numerical codes using the MPS method have been developed. Once dynamic stress distributions can be evaluated at each time step and possible mechanical roles of slope reinforcement may be clarified, then a more efficient slope stabilization system may be achieved, and for instance, positions of ground anchors to reduce the effect of considered dynamic stress concentration can be (visually, i.e., in a more direct way) determined.

Particle methods are essentially based on the classical idea that a deformation may be expressed as the sum of four different types of movement: rigid-body translation; rigid-body rotation; elongation (or contraction); and pure shear, and they evaluate these four independent movements explicitly or implicitly[8]. The methods are extensively used for problems involving large deformations and complex geometries, and they may be

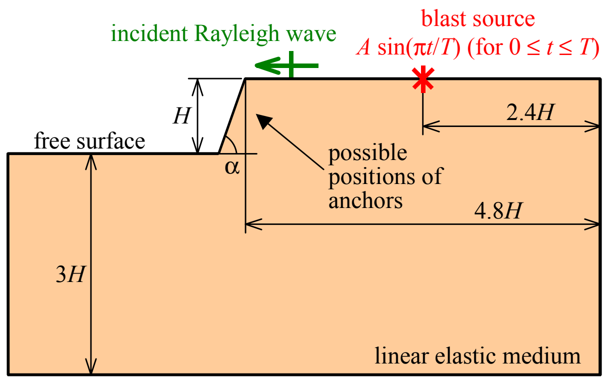



Fig.4 The numerical model for wave interaction with an arbitrarily inclined slope with a convex/concave shape.

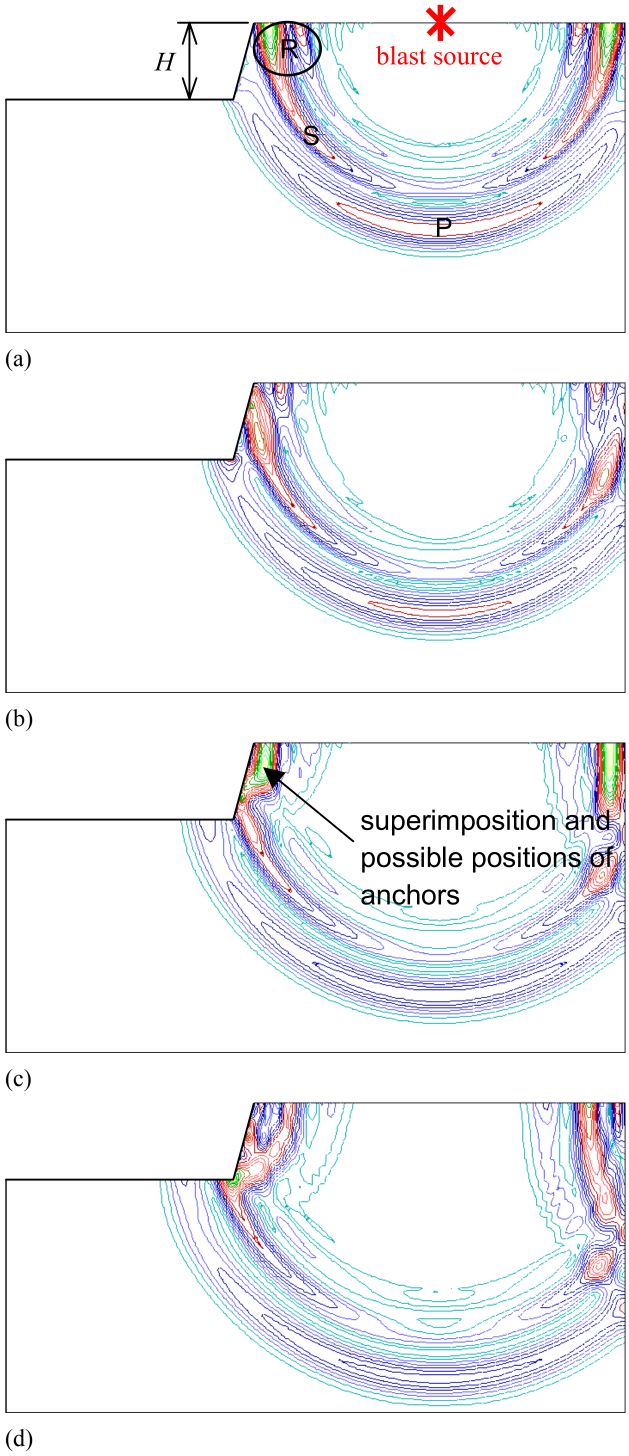
applied to the study of wave dynamics. In the MPS method, the influence of a neighboring particle is evaluated with the "weight" inversely proportional to the particle distance, and it has been reported[9] that simulations involving large deformations and fracture may be performed rather simply by using this MPS method.

The model used in the numerical simulations is shown in Fig.4. A two-dimensional linear elastic medium is assumed and 201 × 101 particles are orthogonally set, with a constant distance between each adjacent particle. The length scale is normalized with the slope height $H$ that is equal to 25 times the particle distance. The upper left particles are removed from the calculations, depending on the slope inclination $\alpha$. Poisson's ratio in the medium is 0.25, and waves are radiated from the blast source that gives a compressive vertical normal stress $A \sin(\pi t/T)$ (for $0 \le t \le T$; otherwise zero) to the source position on the free surface. Here, $t$ is time, and nonnegative $A$ ($T$) is the amplitude (duration) of the stress pulse, respectively. The geometry is selected so that unwanted waves reflected from outer boundaries do not interact with the waves to be investigated.

Figure 5 shows one of the results numerically generated by the MPS method. The snapshots of contours of maximum in-plane shear stress ($\tau_{max}$) are shown. The wave propagation and interaction with the slope ($\alpha = 75°$) is clearly identified where $t$ ($\tau_{max}$) is normalized as $c_R t/H$ ($\tau_{max}/A$), respectively. Here, $c_R$ is the Rayleigh wave speed in the medium, and $c_R T/H$ is set to be 4. Figure 5(a) pertains to the stage where a Rayleigh pulse (non-harmonic wave) propagating to the left is approaching the crest of the slope. Here, longitudinal (P) and shear (S) waves generated by the blast source are also clearly identified but their amplitudes are much smaller than that of the Rayleigh pulse (R). In Fig.5(b), the first part of the Rayleigh pulse is transmitted and it is propagating downwards along the slope face while in Fig.5(c), the latter part of the incident Rayleigh pulse is superimposed with the reflected first part and $\tau_{max}$ is largely amplified, as expected from our analysis in the previous chapter. The primary function of ground anchors is to modify the normal and shear forces acting on potential sliding planes[10]. Hence, possible crack opening in the top and slope collapse due to the (mainly shearing, in this example) action of a Rayleigh surface pulse may be avoided if ground anchors are installed around the positions indicated in Fig.5(c), and the effect of dynamic stress amplification is reduced by them. This reduction of the effect of dynamic surface pulses (waves) might be a rather innovative mechanical role of ground anchors. Exact design parameters of ground anchors, such as design loads, spacing, and so on, may depend on pulse length (wavelength), slope height and other geometrical/material conditions, and they may also be numerically determined to establish a more efficient anchored stabilization system.

Figure 5(d) shows the diffraction of the first part of the pulse around the concave section of the slope. Note that in this numerical simulation surface wave is not harmonic and once the incident pulse has passed the crest there is no interaction between incident and reflected pulses: That is not the case in our harmonic analysis in the previous chapter. In Fig.5(e), the shear wave produced by the diffraction of the first part is visible (SR1), which decays at later stages in Figs. 5(f) and (g) where the diffraction of the latter part of the transmitted pulse emits another shear wave (SR2).

Thus, Rayleigh pulse interaction with a two-dimensional linear elastic slope of an arbitrary shape may be simulated with the numerical codes developed in this study. However, the fundamental numerical simulations performed for wave propagation in a two-dimensional linear elastic plate[11] indicates some questionable points regarding the MPS method: (1) The MPS method has been originally developed in the field of fluid mechanics, and therefore, the effect of shearing in solid may not be fully correctly evaluated; and (2) Strains near surfaces may tend to be smaller than those obtained by other numerical methods (e.g., finite difference method). Careful attention may have to be paid in interpreting the numerical results obtained by the MPS method.



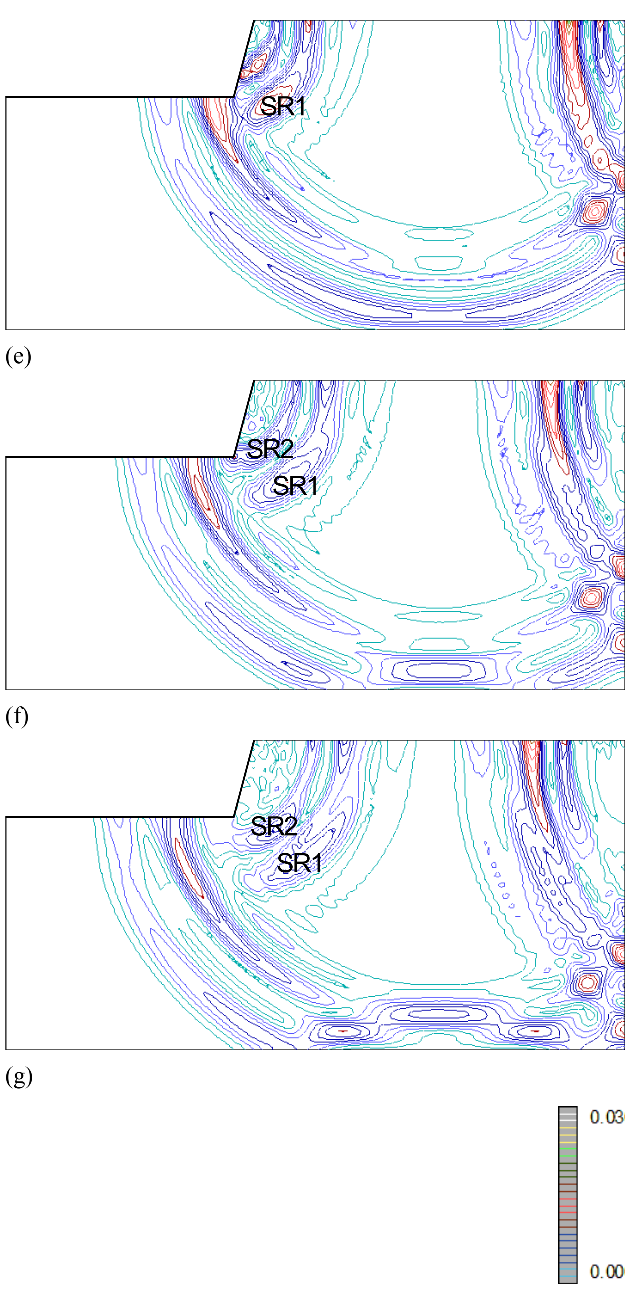




Fig.5 An example of numerical simulations of dynamic wave interaction with a slope. The dynamically induced maximum in-plane shear stress ($\tau_{max}/A$) is shown for the case $c_R T/H = 4$. The slope inclination is 75 degrees. The time $t$ elapsed from the ignition of explosives at the blast source is normalized as $c_R t/H$ = (a) 15.9; (b) 17.5; (c) 19.1; (d) 20.7; (e) 22.3; (f) 23.9; and (g) 25.5.

## 4. Conclusions

The semi-analytical and full numerical investigations into the dynamic behavior of a simple, two-dimensional linear elastic slope subjected to a Rayleigh surface wave (pulse) have provided the following results: (1) The effect of surface wave may be of importance in considering seismically- or blast-induced slope failures; (2) Rayleigh waves can be amplified at the top of the slope most significantly when the slope inclination is about 80 degrees; and (3) Ground anchors are expected to play a fundamental role in more efficiently designing surface-wave-resistant slopes. By repeating simulations like that in Fig.5, precise design parameters may be determined. There are indubitably limitations in the current simple two-dimensional model, but in the theoretically (as well as geometrically) more complex three-dimensional configurations, the effect of Rayleigh waves may become even more significant than that of body waves because of the smaller attenuation of Rayleigh waves with travel distance. Thus, the plain models investigated in the two-dimensional framework may be of certain use in the evaluation of dynamic stability of convex and concave slopes.

Acknowledgments: The financial support by the Japan Anchor Association for the fiscal year 2010 is gratefully acknowledged.

## References


1) Uenishi, K.: On a possible role of Rayleigh surface waves in dynamic slope failures. *Int. J. Geomech.* 10 (4), pp. 153-160, 2010.
2) OYO Corporation: *Miyagi-ken-oki, Japan, Earthquake, June 12, 1978, Damage Investigation Report*, 97 pp., OYO Corporation, 1978 (in Japanese).
3) Uenishi, K., and Rossmanith, H. P.: The relation between stress and particle velocity for Rayleigh pulses. *Acta Mech.* 131, pp. 247-253, 1998.
4) Ashford, S. A., Sitar, N., Lysmer, J., and Deng, N.: Topographic effects on the seismic response of steep slopes. *Bull. Seismol. Soc. Am.* 87, pp. 701-709, 1997.
5) Sitar, N., Clough, G.W., and Bachus, R. C.: (1980). *Behavior of Weakly Cemented Soil Slopes under Static and Seismic Loading*, 150 pp., Stanford University, 1980.
6) Ashford, S.A., and Sitar, N.: Analysis of topographic amplification of inclined shear waves in a steep coastal bluff. *Bull. Seismol. Soc. Am.* 87, pp. 692-700, 1997.
7) Ohtsuki, A., and Harumi, K.: Effect of topography and subsurface inhomogeneities on seismic SV waves. *Earthquake Eng. Struct. Dyn.* 11, pp. 441-462, 1983.
8) Uenishi, K.: Numerical modeling of arrest and resumption of dynamic rupture propagation at material inhomogeneities. *Proc. 2010 Seismol. Soc. Japan Fall Meeting*, P3-37, 2010.
9) Koshizuka, S.: *Particle Method*, 144 pp, Maruzen, 2005 (in Japanese).
10) Wyllie, D.C., and Mah, C.W.: *Rock Slope Engineering Fourth Edition*, 431 pp., Spon Press, 2004.
11) Uenishi, K.: On the numerical analysis of solid dynamics using the moving particle semi-implicit (MPS) method. *Report Res. Ctr. Urban Safety Security, Kobe Univ.* 13, pp. 48-51, 2009.