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Landslides in urban residential slopes induced by strong earthquakes in Japan

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Recent destructive earthquakes in urban regions, such as the 1978 Miyagiken-oki earthquake, the 1995 Kobe earthquake and the 2011 Tohoku earthquake have destabilized many gentle slopes in residential areas of large cities in Japan. Beyond the serious danger to residents of the earthquake affected areas, such landslides revealed the weaknesses of urban development in large cities of Japan. One of the typical large landslides, the Midorigaoka #4 landslide, occurred in residential fills in Sendai city during the 2011 Tohoku earthquake. Inclination measurements in the landslide indicate self-dumping at weak layers in ground structure. Excess pore water pressure in the landslide increased in direct proportion to horizontal peak ground velocity during after-shocks suggesting that the landslide was initiated by the complete loss of shear strength along the slip layer during the main shock. A simple analog model, the roller slider model, can discriminate stable or unstable valley fills during strong motion of past earthquakes. The results of stability analysis by the simplified 3D method based on this model explain the degree of damage in each valley fill during the 2011 Tohoku earthquake. Considering risk mitigation against such landslides in residential lots, urban development should minimize artificial changes in landforms, especially avoiding valley fills. A new concept of a "Counter line city" is proposed that includes both minimization of risk and creating a favorable natural environment.

Introduction: Brief history of landslide disasters in urban regions before 2011

Throughout Japan, large scale residential development on hillsides accompanied by massive grading operations in the suburbs of large cities started in the 1960s. According to Tamura (1977), the decision to expand residential development into hillsides did not adequately consider environmental consequences. The concept of a flat residential lot, which prevailed during the last 2000 years in Japan, was maintained. Thus, residential development into the hillsides consisted of massive grading to create flat land, including, removing hilltops

and infilling valleys. Such massive grading operations often resulted in inadequate compaction of fill materials creating areas of dangerously soft and weak ground within cities throughout Japan. In recent years, a significant number of valley-fill failures and fill slope failures have been reported during large earthquakes that centered in large cities (Kamai et al., 2002). One of the first landslides in a valley-fill was recognized in a suburb of Sendai City during the Miyagi Prefecture earthquake of 1978 (Inst. Geol. Pal., Tohoku Univ., 1979). This trend followed with the Kushiro earthquake of 1993 and the Southern Hyogo Prefecture earthquake of 1995 (Kamai, 1995) (Fig. 1).

Figure 1. Earthquakes caused damage to urban residential region after WW2.

These failures include: (1) failures of most or all of the valley-fill; (2) lateral spreading associated with liquefaction; and (3) development of cracks along the cut and fill transition zones (Tamura et al., 1978; Kamai et al., 2000a; Kamai et al., 2004). These disasters revealed that: (1) many sites within cities were created, having a very high potential for failure; and (2) there is a good possibility that such sites will increase in number with future development. Thus, similar disasters could be repeated if large earthquakes occur near large cities somewhere in Japan. Based on these prior failures, the 2011 landslide disasters in urban regions could have been predicted before the earthquake.

This is a universal phenomenon associated with large scale disasters that can also be observed overseas; Ku-Lin-Ton and Chiuan-Chia-Fu during the Chi-Chi earthquake in Taiwan are some such examples (Kamai et al., 2000b). This paper discusses these highly probable future disasters that may occur under the similar conditions

and offers warnings and guidance for future urban development.

Landslides in urban regions induced by the 2011 Tohoku disaster

The events in 2011 followed similar patterns of damage by landslides in urban regions during past great earthquakes in Japan (Kamai et al., 2013). These recent landslides were distributed from southern Tohoku Province to Tokai village along the Pacific coast of the northern Kanto region; however, landslides were concentrated in the suburbs of Sendai City, the largest city in Tohoku province. In the shadow of the serious damage caused by tsunami waves, more than 200 residential lots in Sendai City were damaged. Among these, at least 50 residential lots were damaged by landslides in the urban residential region, and several hundred houses were destroyed by the landslides (Figs. 2, 3).

While great earthquakes with long recurrence intervals ($M = 8$) have been located off of the east coast of Japan, smaller major earthquakes with $M = 7$ have struck much closer to the mainland with increased frequency and have caused far more damage in these urban regions. Especially, the disaster caused by the 1978 Miyagi Prefecture earthquake is the first case when a modern large city with satellite communities was affected by a major earthquake.

Even after the 1978 Miyagi Prefecture earthquake, the urban region of Sendai City had expanded into hillsides because of population growth, especially during the economic bubble in Japan (1985-1995). In contrast, in other smaller cities, the lesser population growth precluded the need for extensive fill construction for residential lots. Thus, the population dynamics and the process of urban development in the Tohoku province during this half century are reflected in the distribution of urban landslides induced by the 2011 earthquake.

Features of ground surface deformation (i.e. cracks, subsidence, uplifting, and sand boiling) are important evidence to understand the state of landslide movements. These ground surface deformations appeared in conjunction with differences in thickness of fill, age of filling that affects the quality of fills, groundwater level, and existence or non-existence of landslide prevention works. Thus, the following five types of landslides in urban residential fills caused by the 2011 earthquake were recognized:

- Type 1 "Valley-fill type landslide"
- Type 2 "Widening-fill type landslide"
- Type 3 "Failure and deformation in steep sloping fill"
- Type 4 "Complex type of valley-fill type landslide and failure in steep sloping fill"
- Type 5 "Surficial landslide"

Figure 2. Distribution of landslides in urban residential region of southern Tohoku province.

Figure 4 shows slope movement classification of fill slopes from Type 1 to 5, with "thickness of movement mass" on the x-axis and "position of slip surface" on the y-axis. Among the fifty investigated sites, at least 7 sites (about 20%) are known to have been damaged by the 1978 Miyagi prefecture earthquake, indicating that the remediation of such fills was not adequate even after this disaster. Landslides also occurred in relatively newly developed housing lots that were constructed after 1990. Landsliding of fills constructed after the 1980's

Figure 3. Distribution of landslides in Sendai urban region

Figure 4. Types of landslides in urban region caused by the 2011 Tohoku earthquake.

were rare during past earthquake disasters, thus urban landslides in newly developed housing lots are one of the characteristic damages associated with the 2011 earthquake. Type 3 landslides were common in relatively newly developed housing lots during the 2011 earthquake, whereas Type 1 and 2 landslides were mainly distributed in areas developed before 1970. Thus, it appears that ground conditions conducive to sliding existed at the bottom of older fills and these helped generate Type 1 and 2 landslides.

The Midorigaoka #4 landslide

One typical landslide, the Midorigaoka #4 landslide, occurred in the widening fills (Type 2) of the lower part of a subdivision in the Midorigaoka District in the southern Sendai City during the 2011 Tohoku earthquake (Kamai, et.al., 2013) (Fig. 5). This is an older subdivision underlain by Pleistocene volcanic ash deposits (loam textured soils), Pleistocene marine terrace deposits and Pliocene sandstone and mudstone are the basement rocks that contributed to

material (i.e., pumice tuff, sandstone, siltstone) containing intercalated thin lignite beds. The bedrock is hard with N-values ranging from 40 to >50, except for the lignite beds.

Figure 7 shows the plan view and cross section of the Midorigaoka #4 landslide. Tension cracks were aligned along elevation counters at the boundary between the cut and fill. Contractural deformation (e.g. compression cracks, uplifting, and deformation of retaining walls) appeared at the foot of the fill slope on the alluvial valley floor. The fills consist of mixed bedrock material, sand, clay, and sandy silt with gravel. The humid top soil of the original ground surface was found at the boundary of the fill and bedrock. The ground water level was very shallow - 0.5 m to 1.1 m below the ground surface - indicating that the fills were nearly saturated by ground water. The contrast in strength between the fill and bedrock is clear, and soft topsoil exists at the boundary. Thus, the landslide is believed to move along the bottom of the fill. Observations of landslide movements, pore water pressure changes, and seismic response of fills, were conducted in this landslide.

Figure 5. Ground deformation induced by the Midorigaoka #4 landslide in Sendai City. (a) Tension crack at the head. (b) Compressive deformation at the toe.

Figure 6. Columnar sections of bore holes in the Midorigaoka #4 landslide in Sendai City.

Figure 7. Plan view and cross section of the Midorigaoka #4 landslide in Sendai City.

Figure 8. Co-seismic changes of inclination at 3:54 in 31th July 2011.

Landslide movements during earthquake

In the Midorigaoka #4 landslide, measurements of ground inclination using borehole inclinometers, and pore water pressure changes were made from June 2011 until June 2012 with a high precision time interval of 100 Hz. The largest seismic response of inclination was found at the weak layers in topsoils of the base of fills (GL-4m at Bore hole No.1) and in the fragile lignite layer of bedrocks (GL-8m at Bore hole No.2). In contrast, the response in the upper part of fills was small when weak layers developed at the lower portion of fills (Fig. 8). These results indicate the self-dumping effect in the weak layers of the subsurface ground structure. This effect was shown in areas where a thick weak layer developed at the bottom of the fill (borehole No.1 in Figure 8), and in the case of the aftershocks near the hypocenter. This observation indicates that the effects of self-dumping varied depending on the microstructure of landslide and local seismic response. This unique performance of landslide response during an earthquake is a significant finding related to seismic response on unstable slopes.

The horizontal peak ground velocity (PGV) of the estimated waveform of the main shock on 11th March 2011 varied from 90 to 100 cm/s. Observations during aftershocks reveal that excess pore water pressure in the landslide increased in direct proportion to PGV during earthquakes less than 6 cm/s.

According to the linear relationship between PGV and excess pore water pressure in the landslide, excess pore pressure ratio, which is the effective normal stress divided by excess pore pressure during the main shock, might be almost 1.0 considering the effective overburden pressure, from 6 to 8 kPa at this site. This estimation is based on the assumption that this relationship could be applied throughout the strong motion during the main shock. The linear relationship is confirmed by smaller aftershocks until 20 cm/s of PGV (Nishikawa et al., 2002). Assuming this linear relationship during the main shock on 11th March 2011, it infer that the landslide was initiated by the complete loss of shear strength at the slip layer caused by an increase of excess pore water pressure during the strong seismic motion.

Verification of the landslide instability

The roller slider model is an analog to assess instability of valley-fill type landslides in residential regions. The advantage of this model is that it can explain the occurrence of stable valley-fills even during strong motion. This model considers friction along the side walls of

valley-fills. Effects of side walls on valley-fills to constrain sliding movement should be quite important because of the significant reduction of soil strength at the bottom of fills caused by increases in pore water pressure. The analogy of a roller slider at an amusement park is effective to consider the mechanism of the sliding of valley-fills. We can more easily slide down on a wider slider as compared to a narrower one. Thus, the weak layer at the bottom of fill as shown in Fig. 9 should be necessary to represent the slider face in this analog model. There is a high potential of failure at the bottom of valley-fills during strong earthquakes because of the very weak and soft soil that has been identified at the bottoms of some fills where subsurface investigations were performed.

Fig. 10 shows plots of stiffness of fills (mean Vs) versus the ratio of width to depth of valley fills. Obviously, mean Vs of fill is not the predominant factor controlling the occurrence of landslides in fills. In contrast, ratio of width to depth is thought to be a major factor in discriminating between stable and unstable fills during strong seismic motion. It is clear from these case studies that the failure of valley fills is a phenomenon that cannot be determined by a simple 2-

Figure 9. Typical N value of SPT changes in residential fill to original ground (in Ashiya City near Kobe).

Figure 10. Stiffness of fills (mean Vs) vs. Shape ratio (Width/Depth).

dimensional mechanical analysis because the effect of the longitudinal cross-section has to be considered. Thus, the failure mechanism must be analyzed as a 3-dimensional problem. Fig. 11 shows results of stability analyses on fills in 1978 the Miyagi Prefecture earthquake, 1993 Kushiro-oki earthquake and, 1995 Kobe earthquake by both the conventional 2D method and by the simplified 3D method that consider the roller slider model (modified after Ohta and Enokida, 2006). The method selected to assess landslide instability should be able to separate stable and unstable slopes by a factor of safety assessment; the simplified 3D method using the roller slider model (Fig. 11b) is successful in this regard, but the 2D conventional method (Fig. 11a) failed.

Table 1 shows that the factor of safety calculated by the simplified

Figure 11. Results of stability analysis (factor of seismic inertia: $k_h=0.25$). a) 2D Fellenius method b) Simplified 3D method based on the roller slider model

Table 1. Suitability of simplified 3D analysis method based on the roller slider model in the 2011 Tohoku earthquake

Stable				Unstable			
Unit of fills	Degree of damage	Factor of safety	Rating	Unit of fills	Degree of damage	Factor of safety	Rating
A	medium	1.19	x	D	less	1.11	O
B	medium	0.88	O	J	less	1.13	O
C	serious	0.61	⊙	K	less	2.07	⊙
E	low	1.00	O	L	less	1.08	O
F	low	1.01	O	M	less	1.30	⊙
G	serious	0.86	⊙	N	less	1.10	O
H	low	1.15	x	O	less	1.50	⊙
I	low	0.84	O				

3D method could explain the degree of damage in each valley fill in Sendai City (modified after Ohta and Kamai, 2011). The roller slider model is also supported by results of stability analysis using the simplified 3D method in the case of the 2011 Tohoku earthquake.

Lessons learnt from the past earthquake disaster in 1978

A magnitude 7.4 earthquake with an epicenter off the shore of Miyagi Prefecture, northeastern Japan, struck on June 12, 1978, and caused widespread damage to Sendai City and surrounding cities and communities. Damages included 28 deaths, 11,028 injuries, and 179,255 damaged structures. Although the overall damage was moderate, there were a few notable exceptions: (1) damage to the lifelines; (2) fill and cut slope failures; and (3) failure of masonry walls. The first two types of damage occurred in all earthquakes affecting urban areas in Japan after this earthquake in 1978.

Landslides in cut and fill slopes during the 1978 earthquake occurred largely in the Midorigaoka and Nankodai Districts of Sendai City and the Kotobukiyama #4 Subdivision in Shiroishi City. These areas almost overlap with the sites of landslides in 2011. Fig. 12 shows the distribution of landslides in Midorigaoka District in 2011. In this region, landslides in 1978 were recorded in Midorigaoka #1,

Figure 12. Distribution of landslides in the Midorigaoka area in Sendai City.

#2, #3, and #4 (Inst. Geol. Pal., Tohoku Univ., 1979). Among these areas, only the Midorigaoka #1 area was immune to landslide damage in 2011. In Midorigaoka #4, deformation of the ground in 2011, distribution of cracks, areas of subsidence, and uplifting areas experienced almost the same positions and patterns as in the 1978 earthquake. Thus, these landslides should have been expected and preventable if appropriate responses were made after the earthquake in 1978.

Contour line city

The investigation following the March 11, 2011 disaster suggests the intractability of the landslide hazard problem in urban residential fills. Even if artificial valley-fills are appropriately designed and constructed, they will continue to be at risk in urban residential regions in the future. Thus, urban residential lots should be designed to minimize artificial changes in geomorphology, especially avoiding valley fills. In other words, we have to build our houses along the counter lines of hill slopes in seismically active regions.

Fig. 13 shows a thematic drawing of the “Contour line city” (modified after Nagasaka, 2000). Winding roads connect detached houses aligned along the contour lines, and apartment and condominium complexes will be built along surface water streams that pass across artificial drainage. The foundation of buildings should be laid on the stiff original ground. Forested areas consisting of native vegetation should be planted in spaces between buildings; which will contribute rooting strength and remove some subsurface water evapotranspiration. Risk mitigation of slope disasters in urban residential regions should lead to a favorable natural environment in the “Contour line city”.

Conclusions

Landslides in urban residential regions induced by earthquakes including the 2011 off the Pacific coast of Tohoku Earthquake in Japan are discussed. As the result of urbanization, most of these landslides occurred in fills of residential lots in large cities, which have been growing rapidly during the past half century. Results of the investigation of landslides in 2011 are summarized as follows:

- 1 Landslides of fills in residential regions induced by the 2011 earthquake are classified into five types based on the combination of “thickness of movement mass” and “position of slip surface”.
- 2 A simple analog model, the roller slider model, was revalidated to effectively discriminate between stable and unstable valley fills in urban residential regions during strong ground-motion.
- 3 An unique performance of landslides during earthquakes, a self-dumping mechanism at a weak layer at the bottom of fills, was found. This effect varied depending on the microstructure of the landslide and appears to be a significant finding for seismic response on landslide slopes.
- 4 A rapid asymmetric increase in excess pore water pressure during

Figure 13. Thematic drawing of the “Counter line city” (the drawing was modified after Nagasaka, 2000).

strong motion suggests that the landslide was initiated by the complete loss of shear strength via liquefaction of the slip layer at the bottom of fill.

- 5 Some of the locations of landslides in 2011 overlapped with landslide locations in 1978. These landslides are “predictable and preventable disasters” if appropriate responses were made after the earthquake in 1978.

Considering risk mitigation against landslides in residential lots, urban development should be designed to minimize artificial changes in geomorphology, especially avoiding valley fills. A new concept of a “Counter line city” is proposed that includes both minimization of risk and creating a favorable natural environment.

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