Landslides on an ancient Emperor's tomb mound induced by an earthquake in the 16th century

16世紀の地震によって発生した継体天皇陵前方後円墳(今城塚古墳)に認められる地すべりについて

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A landslide that occurred on an Emperor's tomb mound is described and discussed from an engineering geology viewpoint. The remnant horizontal 'fish-scale mosaic' structure of soil blocks that was originally formed may be a valid indicator of the deformation. The main part of the landslide moved a distance of between 2 and 5 m along a slip surface that was inclined 1 to 3 degrees against the dip of the mound. The toe fell into an adjacent moat as a slump and became a rapid earth flow that filled the moat. The 'Keicho-Fushimi' earthquake of 5 September 1596 is considered to have triggered the landslides which deformed the Imashiro-zuka Emperor's tomb mound. The cumulative permanent displacement was estimated by Newmark's method. The estimated permanent displacement of approximately 200 cm is the lower limit of the geological cross-section observed. This is a good approximation given that the landslide occurred four hundred years ago and considering the limitations of information based on deformations, swelling of clay minerals, smectite, groundwater, and drainage measures.
***Key Words*：** *landslide, earthquake, archaeological research, tomb mound, kofun*

1. INTRODUCTION

'Kofun', keyhole-shaped tomb mounds, are famous monuments of ancient East Asia, found mainly in Korea and Japan. They are impressive large-scale fill structures, and were constructed only during the 300 years between the 3rd century and the 6th century AD. These kinds of tomb mounds were typical of ancient powerful clans or Emperors who were at the top of the hierarchy of ancient society. The Imashiro-zuka mound is one of the largest tomb mounds of the 6th century in the northern Osaka region. Based on archaeological research, it is considered to be the tumulus of the Great Emperor Keitai who died in 531 AD (Miyazaki, 2000).

The Imperial Household Agency of the Japanese Government has selected and listed Emperors' tumuli from among many tomb mounds that were located in the ancient capitals of Japan. The government intends to preserve Emperors' tumuli from any excavation, and does not give permission for research on Emperors' tumuli. The Imashiro-zuka mound has fortunately failed to be listed by the Imperial Household Agency as an Emperor's tumulus because of its deformed shape. Instead of the Imashiro-zuka mound, a mound of better shape was officially appointed as the Emperor Keitai's tumulus.

Archaeological research on the Imashiro-zuka mound started in 1996, the first detailed research on an Emperor's tomb mound, and remarkable achievements have been made. In the autumn of 2000, it was discovered that a landslide had drastically deformed the tomb mound (Shuzui et al., 2000).

In this paper, a geological description of landslides on ancient tomb mounds (Kofun) is presented, and a simple model of the landslide on the Imashiro-zuka mound, one of the most important historical heritage sites in Japan, is discussed.

2. STRUCTURE OF THE EMPEROR'S TOMB MOUND

The Imashiro-zuka mound was built on an alluvial plain in Takatsuki City, in the northern part of the Osaka region. The capital of the Yamato dynasty (ancient Japan) was located close to the Imashiro-zuka mound in the first half of the 6th century. One of the most active faults in Japan, the 'Arima-Takatsuki tectonic line', runs beneath the Imashiro-zuka mound, which means that the Imashiro-zuka mound is one of the largest fill structures located in the region of the highest seismic activity in the world.

The plan view of the Imashiro-zuka mound is keyhole shaped. This is the most popular and original shape of ancient tomb mounds in Japan, a combination of a rectangular shape at the front and a round shape at the back of the mound. The tomb, 186 m long and 10 to 15 m high, is surrounded by a double water-

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filled moat 1 to 4 m deep. The mound sustained an artificial landform change by the Load Nobunaga in the 16th century. He constructed a fortress for his corps on the mound.

Horizontally layered small soil blocks of 40 cm width and 10 cm thickness built up the fill of the mound. The remains of 'scaly mosaic' (fish skin) structures corresponding to each soil block are observed almost horizontally in the non-disturbed part of the mound. These soil blocks, produced from mixtures of silt, clay and charcoal, were thoroughly consolidated by being rammed hard, and were even difficult to excavate by bulldozer. The wet density of soil blocks ranges from 2.02 to 2.06 g/cm3, and the range of void ratio is from 0.514 to 0.561 (Shuzui et al., 2000). Four trenches were dug on the mound for the archaeological survey. The trench investigation revealed that the base of the mound inclined slightly to the central part of the mound. It appears that the inclination of the base is caused by ground subsidence in alluvial clayey deposits under the excess load of the mound.

3. LANDSLIDE

(1) DISTRIBUTION

Five landslide blocks developed on the slope of the tomb mound. A trench related to the archaeological survey of 2000 traversed one of these (block # 2) longitudinally. A geological cross-section of # 2 landslide mass with a length of 60 m and a width of 50 m was clearly observed along this trench. The foot of the landslide, the accumulation region, spread across the inner water-filled moat from the edge of the mound slope. It has a limited vertical displacement of 1 to 2 m, because of the non-rotational movement of the landslide. The head scarp developed in obscurity. The depth of the slip surface is between 2 and 6 m.

(2) STRUCTURE

1) The 'scaly mosaic' structure of soil blocks

The tomb mound is composed of an accumulation of well-consolidated small soil blocks that are stacked together to form the 'scaly mosaic' (fish skin) structure' in almost horizontal layers. Thus, the deformation of the horizontal units of the scaly mosaic structure is a valid indicator of the deformation caused by the landslide and the artificial disturbance of the mound. Figure 5 is a sketch showing the geology along a lateral wall of the trench.

2) Slip surface

A slip surface developed mainly along the boundary between the original ground surface and the fill of the tomb mound. The base of the tomb mound dips slightly to the centre (the core) from the rim of the mound, therefore the slip surface in the upper part of the landslide is inclined at 1 to 3 degrees towards the centre. This is in the opposite direction to the landslide movement.

There are two horizons of slip surfaces in the main part of the landslide. The upper slip surface has a horizontal shear zone of 1 to 3 cm thickness in which soil blocks are thinly elongated. The trace of the upper slip surface continues for about 15 m along the base of the mound, and is limited in the main body of the landslide. The lower slip surface is a smooth shear surface cutting alluvial soft blue-coloured clay, and lies about 10 cm beneath the upper slip surface. The continuity of the lower slip surface is better than that of the upper slip surface. It can be considered that the shaking of the earthquake initially formed the upper slip surface, and the landslide body was replaced along the lower slip surface.

Based on both the elongate structure of soil in the shear zone and the blue-coloured alluvial clay of the original ground beneath the lower slip surface, the ground water table at the landslide movement can be considered to be higher than the upper slip surface.

3) Deformation of main part

The original scaly mosaic structure is maintained almost horizontally in the main part of the landslide mass. Coherent landslide movement along the almost-horizontal slip surface can be recognized based on the slight deformation in this part. In the head (upper part) of the landslide, the scaly mosaic structure of the filling material is inclined steeply towards the central part of the mound. The structure dips at up to 50-70 degrees. It is considered that the upper part of the head of the coherent landslide body fell with a rotational movement (toppling) into the open space that was formed by the landslide movement. The opposite inclination of the slip surface was convenient for that movement (toppling). The toppling of the upper part of the head occurred immediately after the initial landslide movement.

Several minor gravitational faults developed in the lower part of the main body of the landslide. These faults have a net slip (vertical dislocation) of up to 4 cm, cut the upper slip surface, and continue to the lower slip surface. This means that these gravitational minor faults are younger than the initial landslide movement, which formed the opposite inclined upper slip surface. The gravitational faults are concentrated in the part that was the shoulder of the bank of the inner moat existing before the landslide event.

4) The secondary slide and its associated earth flow

The inner moat was filled by the secondary slide and its associated earth flow deposits. The secondary slide was separated from the main landslide on the bank of the inner moat that existed before the landslide, and fell into the moat along its inner flank. The structure of the soil blocks indicates that the head of the secondary slide toppled forward, and the lower half of the slide moved as a rotational slump that fell into the water-filled moat.

The foot of the secondary slide flowed into the ditch, which has a width of 5 m and a depth of 1.2 m. This ditch was artificially made at the moat floor in the Middle Ages (13th to 16th century), and had been filled with thick muddy deposits. The deposits were eroded by the foot of the slide, and rolled up vigorously in water. The underwater turbidity flow consisted of the sliding blocks and muddy deposits pouring out rapidly from the ditch, and rolling horizontally across the inner moat. The flow reached to the opposite side of the moat, and its tip bent upward slightly along the flank to terminate.

(3) MECHANISM

1) Seismic deformation of main part of the landslide

Newmark's method

Two unique features characterized the landslide of the Imashiro-zuka mound: the opposite-inclined slip surface and the slide which changed to a rapid earth flow. Based upon Newmark's method, we would like to explain the ground displacement caused by landslide motion. Newmark (1965) proposed modelling a slope subjected to earthquake-induced accelerations as a friction block resting on a slip surface subjected to the same accelerations as the modelled slope. Therefore, in each instance when the sum of the static and the dynamic forces exceeds the shear resistance of the slip surface, the slope will displace. The sliding-block analogy assumes that the slope consists of rigid and perfectly plastic materials. The material of the main body of the Imashiro-zuka landslide is composed of well-consolidated and rigid soils that are not very common as filling material. Therefore, each assumption is capable of being accepted in the case of permanent displacement analysis on the main part of the Imashiro-zuka landslide.

The critical acceleration

Newmark originally employed an energy-based method for calculating cumulative slope displacement. A less numerically cumbersome method was developed by Wilson and Keefer (1983), where those parts of an earthquake accelerogram that exceed the critical acceleration (α c) of a slope are double integrated. The critical acceleration (α c) should be estimated by back analysis of static slope stability. The factor of safety during an earthquake is calculated by the following equations.

$$Fs = \frac{\sum\left[c_{cu}l + \{(W - k_v - ub)\cos\theta - k_h W \sin\theta\}\tan\phi_{cu}\right]}{\sum\{(1-k_v)W\sin\theta + k_h W\cos\theta\}} \qquad (1)$$

These are based on a simple relationship between the force balances just at the time that the landslide collapsed as a result of the earthquake. As shown in Figures 3 and 4, the main slip surface developed in alluvial blue-coloured (iron-hydroxide-coloured) clay that was usually beneath the ground water table. In this case, we can use $\phi cu = 0^\circ$ for soft saturated clay that should be sheared in an undrained condition during shaking due to the earthquake. In this case, the factor of safety (Fs) can be expressed as

$$Fs = \frac{\sum c_{cu}l}{\sum\{(1-k_v)W\sin\theta + k_h W\cos\theta\}} \qquad (2)$$

where ccu = 42 kN/m^2 (1.2 times the static cohesion) can be used as dynamic shear strength for the stability analysis. The static shear strength (cohesion) was estimated from the relationship between N values and unconfined compression strength (*qu*) of the alluvial clay (Japan Geotechnical Society, 1995). A critical acceleration α c = 0.46 g corresponding to the critical failure condition of the slope (*Fs* = 1.0) was calculated for the main part of the Imashiro-zuka landslide, which has an almost horizontal slip surface ($\theta = 0$).

Earthquake records

The most difficult aspect of conducting a Newmark analysis is selecting an input ground motion. Selecting a time history requires some knowledge of the shaking characteristics. Archaeological evidence shows that the inner moat was filled between the 13th and 16th centuries. In the northern Osaka region, the only earthquake during this period that had an intensity of over 0.46 g was the 'Keicho-Fushimi' earthquake of 5 September 1596 (Usami, 1996). The Keicho-Fushimi earthquake resulted from the tectonic movements of the Rokko and the Arima-Takatuki tectonic lines, and was similar to the Kobe earthquake of 1995 (Sangawa, 2000).

The Japan Meteorological Agency's (JMA's) Kobe observatory has almost the same geological conditions as the site of Imashiro-zuka that was very close to the hypocentre of the Keicho-Fushimi earthquake. The strong movement characteristics at the Imashiro-zuka site, maximum velocity and spectrum etc., might be similar to the strong movement record collected at the JMA observatory (Kobe NS) located in the high-shaking-intensity zone of the 1995 Kobe earthquake. Therefore, the earthquake accelerogram record of the Kobe earthquake might be best for the estimation of landslide displacement using Newmark's method.

Permanent displacement

Once the critical acceleration of the Imashiro-zuka landslide has been determined and acceleration-time histories have been selected, permanent displacement can be calculated by doubly integrating those parts of the strong-motion record that lie above the critical acceleration (Wilson and Keefer, 1983). Figure 6 shows the critical acceleration superimposed on the earthquake accelerogram (JMA Kobe NS) of the 1995 Kobe earthquake, the integrated velocity-time history, and cumulative displacement of the sliding block.

This double integration process was conducted on the following assumptions:

i) The mobilized ccu after the displacement reached 100 cm was reduced to 90% of static cohesion, taking into consideration the disturbance resulting from the large displacement.

ii) The critical acceleration of 0.35 g was used after 7 sec in the strong-motion time series, corresponding to changes mobilized ccu by the large displacement of 100 cm.

iii) The block was able to move to the both directions, to the downward of slope and to the upward.

iv) The landslide velocity will not force to be zero during the movement, if the acceleration will be below the critical acceleration (α c). The integration of acceleration will be continuing until the calculated velocity equal to be zero, corresponding to the rapid increase of pore water pressure and the effect of momentum of inertia during the landslide movement.

The calculation shows that the cumulative permanent displacement would have reached about 200 cm after the main shaking. Geological evidence shows that the main part of the Imashiro-zuka landslide moved a distance of between 2 and 5 m, as shown in Fig. 5. The estimation by Newmark analysis agrees with the lower limit of the cross-sectional geological observation, which will be a sufficient approximation given by the insufficient information on a landslide which originated four hundreds years ago

2) Process of sliding

The external force necessary to produce a landslide that had an opposite-inclined slip surface would be so great that a strong earthquake tremor is considered to have triggered the landslide. It is possible to follow the process of landslide activity by using the deformation of the original scaly mosaic structure of soil blocks as the tracer. Over a short period of time, the three stages of landslide activity advanced as follows.

i) Separation from the tomb mound

Vertical open cracks were formed at the foot of the mound by strong earthquake tremors. Some blocks were separated from the tomb mound by deep vertical cracks. Five of the separated blocks developed to landslides after the following process.

ii) Landslide movement along the reverse-sloping slip surface

A shear surface was formed by out-of-phase tremor motion along the boundary between the original ground and the tomb mound. This shear surface became the slip surface of the landslide. The landslide moved a distance of between 2 and 5 m along the opposite-inclined slip surface. A smooth slip surface was formed by this large displacement.

iii) Movements after the initial sliding

The lower part of the landslide that stuck out on the inner moat fell into the mud-filled ditch as a rotational slump. This slump changed to a rapid flow slide, and filled the inner moat. The shoulder of the bank of the moat became a region of tension, and a minor gravitational fault system formed in this part. The space formed by the landslide, between the head and the main scarp, was filled by the 'backward toppling' of the upper part of the head of the landslide.

4. CONCLUSIONS

This study has described and discussed the landslide in an Emperor's tomb mound from an engineering geology viewpoint. The following remarks are concluded.

i) It was possible to follow the landslide activity by using the deformation of the scaly mosaic structure of soil blocks that were horizontally layered before landsliding occurred.

ii) The main part of the landslide moved a distance of between 2 and 5 m along the opposite inclined slip surface. A rapid flow slide filling the inner moat derived from the toe that fell into the inner moat as a slump. The rear part of the head of the main landslide toppled backward, and filled the space that was formed by the landslide between the head and the main scarp.

iii) The cumulative permanent displacement was estimated by Newmark's method. This would have reached about 200 cm after the main tremors. Geological evidence shows that the main part of the Imashiro-zuka landslide moved a distance of between 2 and 5 m. The estimation by Newmark analysis agrees with the lower limit of the geological observation, and will be a sufficient approximation given by the insufficient information on a landslide which originated four hundreds years ago.

iv) The 'Keicho-Fushimi' earthquake of 5 September 1596 was the major earthquake occurring in the northern Osaka region after the 13th century. This earthquake is considered to have triggered the landslides which deformed the Imashiro-zuka Emperor's tomb mound. The Imashiro-zuka mound is not only a site of ancient historical heritage as an Emperor's tomb mound, but also a monument to a major earthquake that seriously affected social and economic activities in 16th-century Japan.

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References

1） Japan Geotechnical Society. 1995. Geotechnical exploration manual. Tokyo, Japan Geotechnical Society.

2） Miyazaki, Y. 2000. The 4th archaeological study on the 'Imashiro-zuka' tomb mound, Explanatory text for site tour. Takatsuki, Cultural Heritage Division of Takatsuki City. [in Japanese]

3） Newmark, N. M. 1965. Effects of earthquake on dams and embankments, Geotechnique, 15, pp. 139-160.

4） Okada, A., Uemura, Y., Togou, M., Nakata, T. and Watanabe, M. 1996. 1:25000 active fault map in urban area 'KYOTOSEINANBU'. Tsukuba, Geographical Survey of Japan.

5） Sangawa, A. 2000. Records of ground disaster on archaeological sites. Disaster Prevention Research Institute Symposium. [in Japanese]

6） Shuzui, H., Kamai, T. and Fukuoka, H. 2000. Causes and distribution of landslides on the tomb mound of the Emperor "Keitai". Disaster Prevention Research Institute Symposium. [in Japanese]

7） Usami, T. 1996. Materials for comprehensive list of destructive earthquakes in Japan. Tokyo, University of Tokyo Press.

8） Wilson, R. C. and Keefer, D. K. 1983. Dynamic analysis of a slope failure from the August 1979 Coyote Lake, California, earthquake, Bulletin of the Seismological Society of America, 73, pp. 863-877.

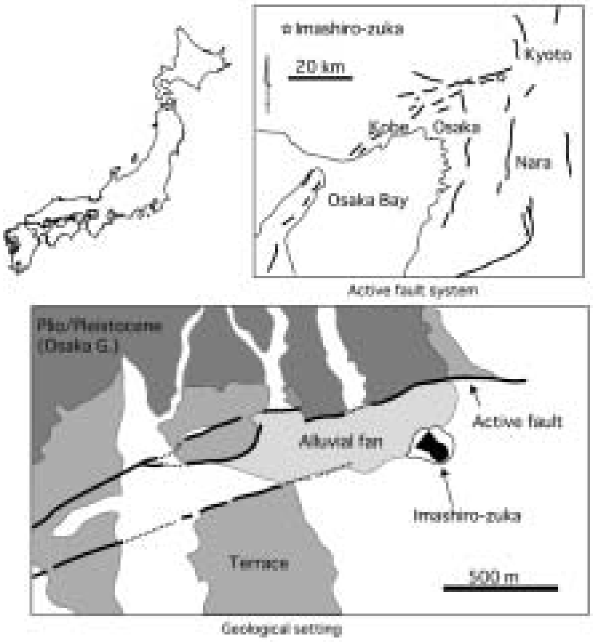

Fig.1. Location and geological setting of the Imashiro-zuka mound (geological map was after Okada et al., 1996).

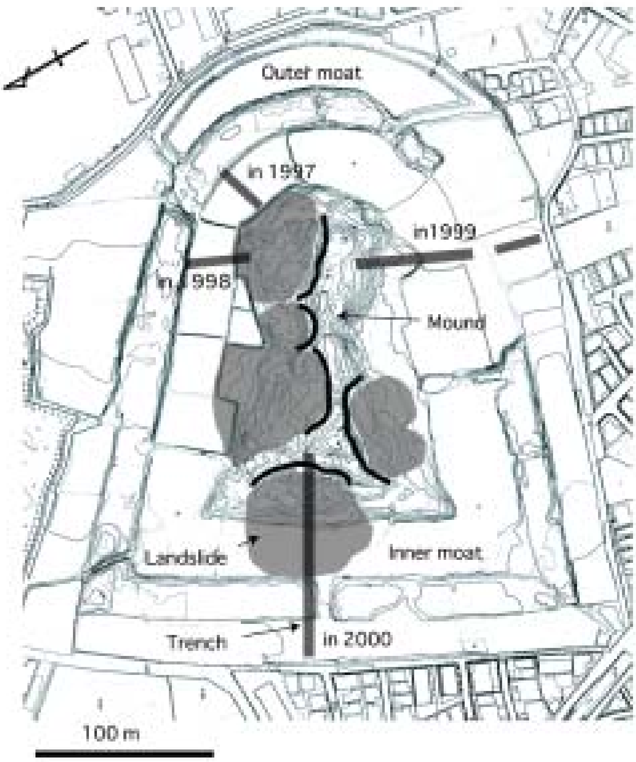

Fig.2. Plan view and landslide distribution in the Imashiro-zuka mound.

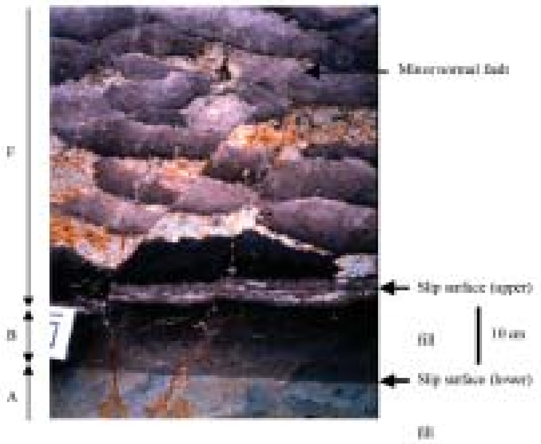

Fig.3. Close-up of the slip surfaces and the remaining 'scaly mosaic' (fish skin) structure of soil blocks.
F: Material filling the mound; B: Black (organic) soil, pre-6th century;
A: Alluvial clay (blue)

Fig.4. The landslide observed along the trench in 2000. The landslide mass (secondary slide) fell into the inner moat. The base of the mound (the slip surface of the main block) is inclined at 1-3 degrees towards the centre of the mound as a result of the ground subsidence in alluvial clayey deposits under the excess load of the mound. (Photo by Dr. Sangawa)

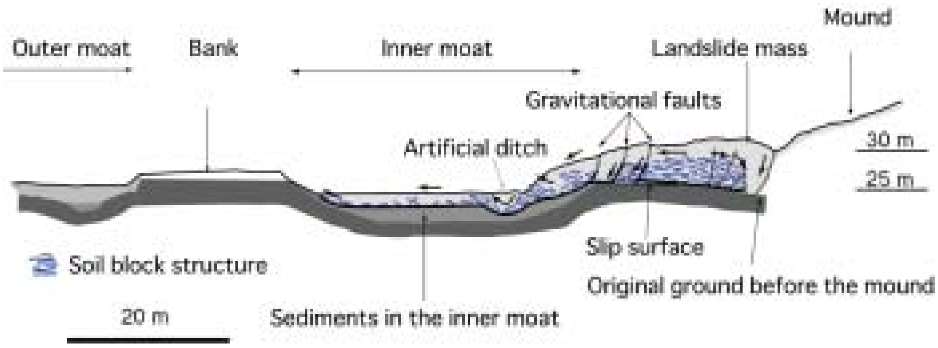

Fig.5. Cross-section of the landslide along the trench in 2000.

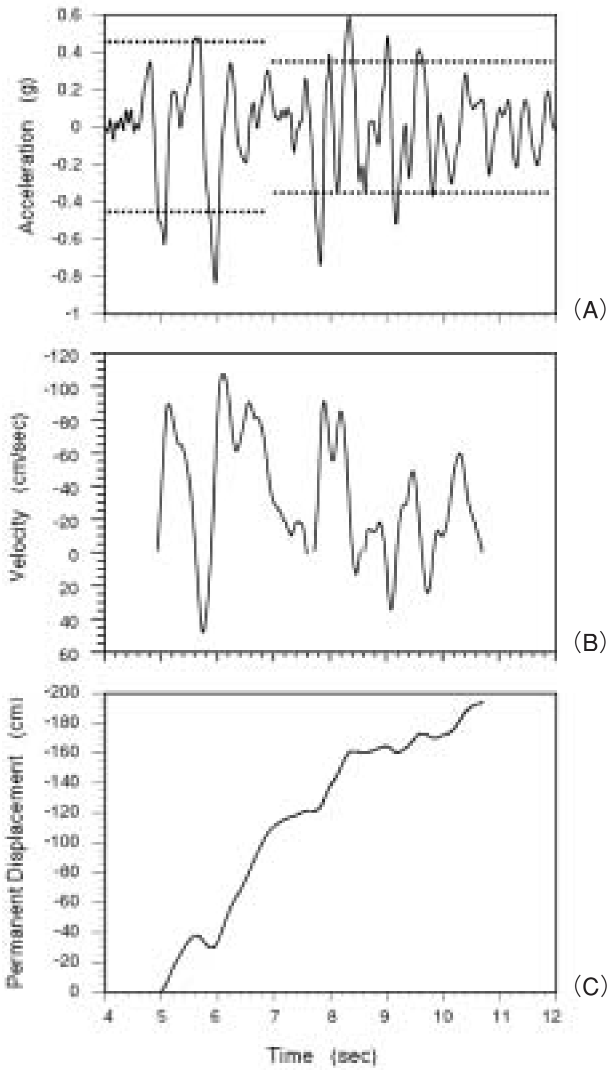

Fig.6. Results of the Newmark analysis.
(A) Earthquake acceleration-time history with critical acceleration (Kobe earthquake NS). The critical acceleration was reduced after 7 sec in the strong-motion time series corresponding to the large displacement of 100 cm.
(B) Velocity of landslide block vs. time
(C) Displacement of landslide block vs. time

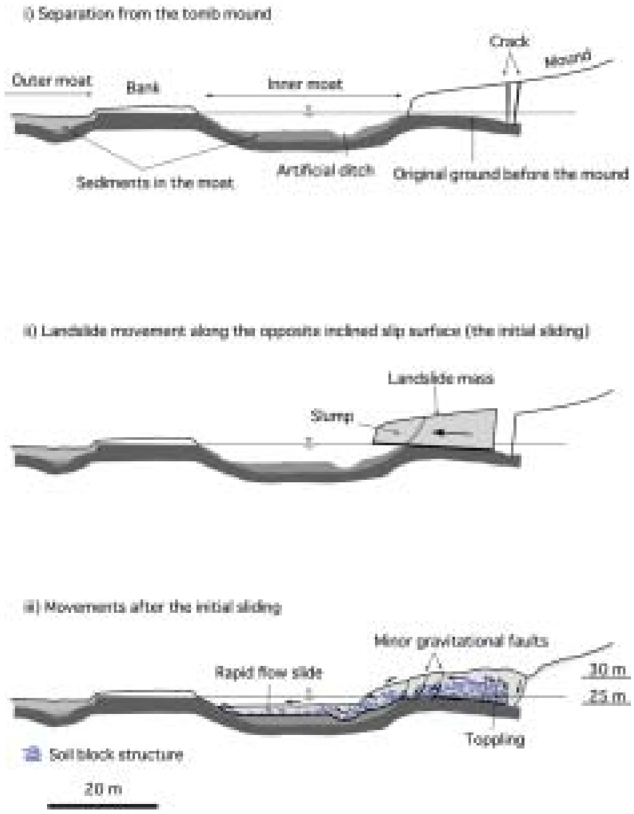

Fig.7. Process of collapse within the landslide.