A Countermeasure For Slope Safety Focusing On Earthquake Motion Amplification In Filling Valleys

Ohashi Tadashi
Kiso-jiban Consultants Co., Ltd. ,Japan

Sugito Masata
Gifu University, Japan

SUMMARY
As one of the reasons of extensive damage caused during earthquakes to roads and residential lands located on filling valleys, effects of amplification of earthquake vibration have been pointed out. In this paper, the authors highlight, with FEM analyses, the effects of the transverse cross sectional geometry of the valleys on the slope stability during earthquakes. As results of research, the investigation shows that slope stability of the valley fill depends not only on the earthquake vibration response in the valley axis direction but also on the amplification of the vibration associated with the cross-sectional shape of the valley. This Idea is applied to the slope failure that occurred at the filled valley along the road during the Noto Hanto Earthquake in 2007. The example demonstrates the effectiveness of the proposed method and illustrates necessity to adequately include the effect of the valley geometry in the stability evaluation and countermeasure of slope stability.

Keywords: Earthquake motion amplification, Slope safety in filling valley, Countermeasure

1. GENERAL INSTRUCTIONS

The amplification of earthquake motion and slope safety assessment in the direction of valley axis are often reported. There are few studies on the influence of the cross-sectional valley shape for slope stability. In this paper, the authors highlight, with 2-D FEM analysis, the effects of the transverse cross-sectional geometry of the valleys on the slope stability during earthquakes. The study shows that the amplification of the acceleration during earthquakes is greatly related to valley width, valley depth.

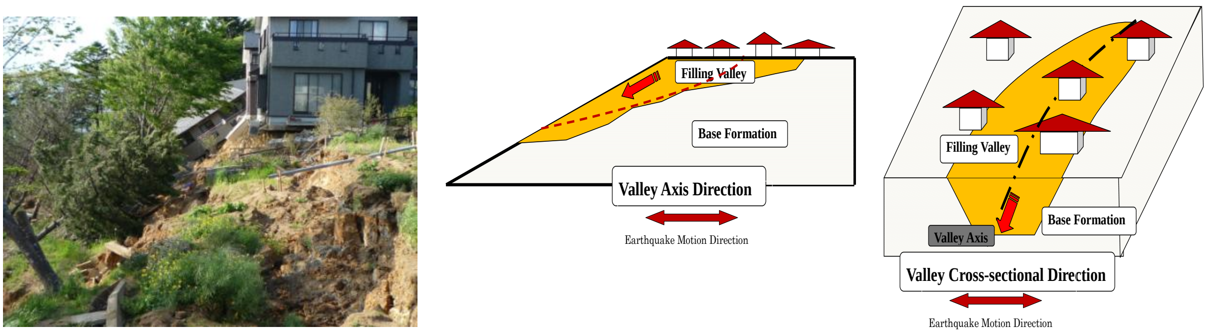


Figure 1. Fill slope failure. (The 2011 off the Pacific coast of Tohoku Earthquake)
Left panel:valley axis direction. Right panel:valley cross-sectional direction.

As results of research, the investigation shows that slope stability of the valley fill depends not only on the earthquake motion response in the valley axis direction but also on the amplification of the motion associated with the transverse cross-sectional shape of the valley. In evaluating slope stability, two components of the motions are considered and superimposed as shown in Figure-1; the first is the seismic ground motion in the direction of the valley axis without considering the geometry effects, and the second is motion that induced by the transverse cross-sectional shape of the valley. This technique is applied to the slope failure that occurred at the filled valley along the Noto Toll Road during the Noto Hanto Earthquake in 2007.The study shows that while the safety factor of the slope without considering the geometry effects is above unity, it is below unity with consideration of the geometry effects, with several percent of reduction in the factor of safety. The example demonstrates the effectiveness of the proposed method and illustrates necessity to adequately include the effect of the valley geometry(the transverse cross-sectional shape of the valley) in the stability evaluation and countermeasure of slope stability.

2. INFLUENCE OF SEISMIC GROUND MOTION INTERFERENCE IN FILLING VALLEYS

2.1. Analytical Model

Two dimension finite element analysis model (2D) of the fill constructed on the base that inclines irregularly is shown in Figure-2. The characteristic of the amplification caused by geometrical interference of the seismic ground motion is evaluated by performing the case study that using this 2D model. There are two patterns in the models, and one is a valley axis direction model, and another one is a transverse cross-sectional shape of the valley. The energy transmission boundaries were set to the both-sides as a boundary condition, and the viscous boundary was set to the bottom. The impedance ratio is assumed to be about 0.16.The shear wave velocity of the fill ground (① layer) and the base rock (② layer) is assumed to be Vs_1=100m/s and Vs_2=500m/s. The unit weight of each layers are assumed to be γ_1=17.6kN/m^3 and γ_2=21 .6kN/m^3. The nonlinearity in a dynamic stress-strain relation of the fill ground is not considered in this model in order to confirm the geometrical influence of the seismic wave movement. The damping ratio was assumed to be constant 2%.

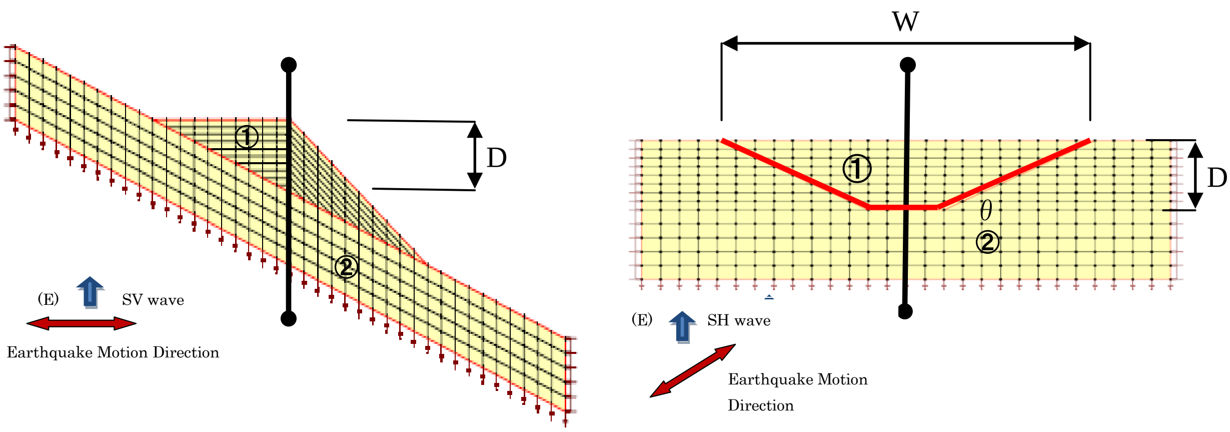


Figure 2. 2D models for each direction of fill valley. Left panel : Valley axis direction. Right panel : Valley cross-sectional direction.

The layer thickness of the fill decided to be called D, and to call the width of the valley W. The slope gradient θ in the valley of the transverse cross-sectional direction was set to 18.5°, 26.5°, and 45°. D was assumed to be constant (15m), width W of the valley was changed to 45m,75m,120m.We considered shape ratio W/D in this study (Kamalian et al.2008).

The amplification of the seismic ground motion by geometrical shape of the valley was calculated. SV-wave was set as an incident seismic wave for the valley axis model, and the SH-wave was set in the valley transverse cross-sectional model respectively. Here, SV-wave is shaking of the plane direction in 2D model, and SH-wave is that of the anti-plane direction. This reason is that the failure on the slope of the fills is usually occurred in the valley axis direction, and the direction of the shake of the SH-wave in the transverse cross-sectional valley is the same direction of the movement of the slope failure for the valley axis. An incident wave of two models set in the sine wave of 1Hz as half wavelength, and set the acceleration amplitude to 100gal. Seismic wave incident depth assumes GL-15m to be a position from former ground level on a bed rock with the valley axis model and the valley cross sectional model respectively.

2.2. Analytical Result

The analytical results are show in Figure-3. The amplification of SV-wave was confirmed in the upper part of the fill in the valley axis section, as a current research is pointed out, and the maximal acceleration is 370gal in the present study (left panel). Incident acceleration SH-wave is considered for valley transverse cross-sectional direction in this study (right panel). The high frequency is superior by the influence to which the fill ground is restrained by the base on both sides of the valley, and displacement (strain) decreases by incident acceleration SV-wave. Therefore, it is considered that the influence in slope stability of the direction of the valley axis by SV-wave in valley transverse cross-sectional direction is a little because of the difference of the direction of the shake. On the other hand, the fill slope failure is usually generated in the direction of the valley axis. Therefore, the direction of the shake of the anti-plane SH-wave of the valley transverse cross section is corresponding in the direction of the slope failure, and the acceleration and displacement are assumed to be amplification in the direction of the valley axis. One example of the response calculation result of W/D=5 and θ=26.5° in the valley transverse crossing section is shown in Figure-3(right panel). Incidence SH wave of 1Hz sine half wavelength that became the same direction as the direction of the amplitude in the valley axis section was input to the base by 100gal. It was confirmed that the maximal acceleration of the fill ground is 420gal versus input outcrop acceleration 2E (200gal).

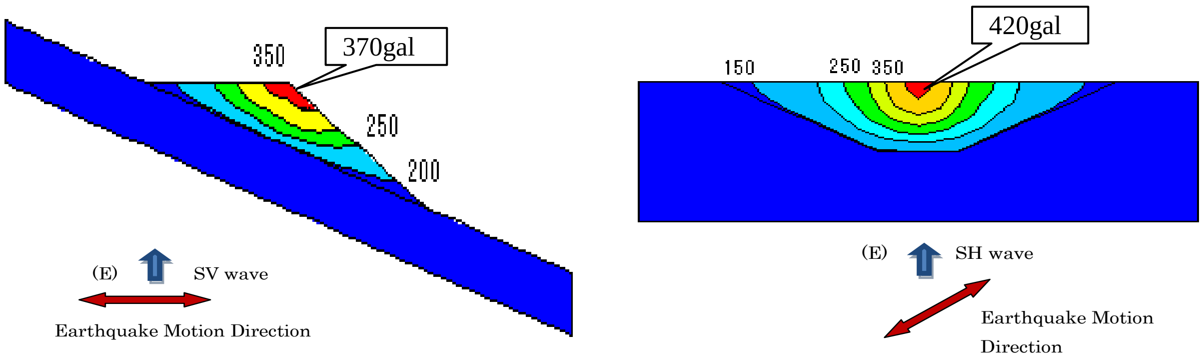


Figure 3. Example of analytical results for each direction of fill valley. Left panel :Valley axis direction. Right panel : Valley transverse cross-sectional direction.

Figure-4(left panel) shows the ratio (amplification rate from the base) to amplitude (2E) of the incidence of the ground level acceleration in the valley transverse crossing section of W/D=8.The case with W/D=8 shows the difference of amplification when the valley inclination corner θ is set to 18.5°, 26.5°, and 45° respectively. In the case with W/D=8 and θ=45°, the amplification of the acceleration is peaks in two places of the vicinity of the point of contact of the slope and the bottom in a valley transverse cross-sectional direction. And, the range of amplification of the acceleration exists in the center part of the valley fill when θ is 26.5° and 18.5°.

We defined the ratio of the acceleration amplification which caused from the irregular ground (2D)and the horizontal ground(1D) as β (Assimaki et al.2005). In the condition such as the physical properties values and 1Hz SH incident waves, β was 1.1-1.25 in the range of W/D=3-8 as shown in Figure-4 (right panel). Especially, we can be seen to amplify with about W/D=5 greatly in the focusing effect by overlapping wave motion from the slope of valley transverse cross-sectional direction. In the case with W/D=8, neither the wave transmitted below directly nor the wave refracted from the one side slope overlap at the center. On the other hand, it is considered that it became large amplification because overlapping a wavy peak of the wave propagated directly and a wavy peak of the wave refracted from the both sides of the valley slope is strong in the case with W/D=5.

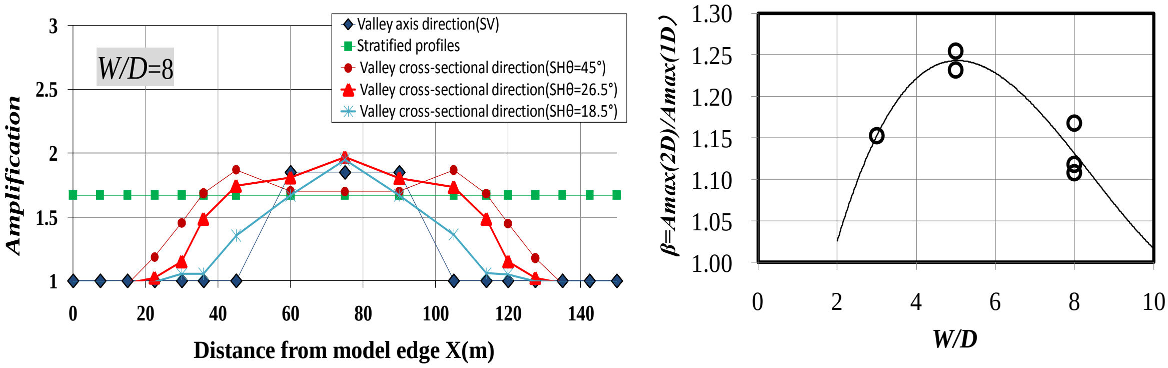
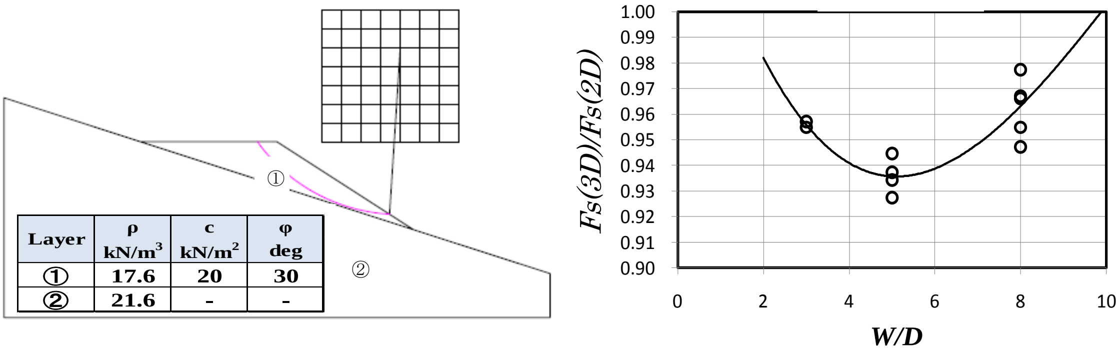


Figure 4. The ratio to amplitude (2E) of the propagating incidence wave in the valley transverse crossing section of W/D=8 (left panel). Relationship between W/D to β (right panel).

3. STABILITY EVALUATION OF FILL SLOPE ON WHICH SEISMIC GROUND MOTION AMPLIFIED BY FOCUSING EFFECT

The slope stability calculation by the circular arc method was performed to consider the seismic ground motion amplification by the tilt angle θ in a valley transverse cross-sectional direction and W/D. The ground conditions assumed to be c=20kN/m^2 and φ=30° in the fill layer (①layer). The groundwater is not considered. The seismic force (0.6-0.75 times maximal acceleration Amax (SV) of each depth) was made to act on the clod center of gravity and the circular slide was calculated for the valley axis model. Moreover, the base rock layer (②layer)was assumed not to failure. The example of calculating slope stability is shown in Figure-5 (left panel). The safety factor of slope stability due to the pseudo-static force in the valley axis section was defined as Fs (2D). The safety factor of approximate 3D that surcharged by β on irregularly condition (W/D) was defined as Fs (3D).



Layer	ρ kN/m^3	c kN/m^2	φ deg
①	17.6	20	30
②	21.6	-	-

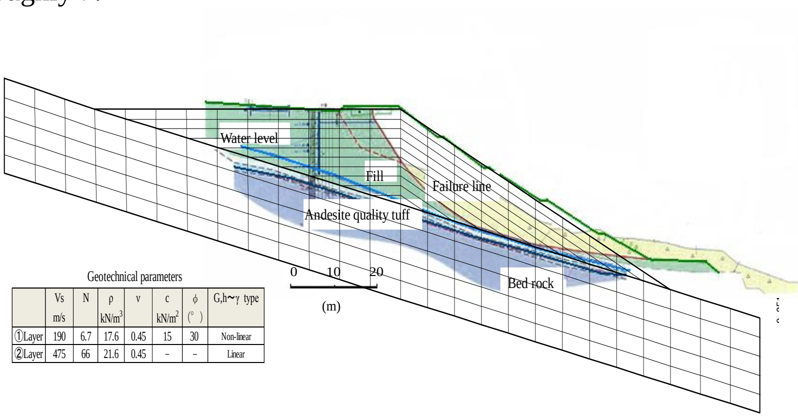
Figure 5. The model of slope stability (left panel), and Relation between W/D to Fs (3D/2D)(right panel)

Figure-5(right panel) is a comparison of Fs (2D) and Fs (3D). According to the applied limit equilibrium theory the here used ratio is significant only if Fs(2D) and Fs(3D) are higher than 1 respectively. Therefore, the comparison of the safety factor is not strict. The safety factor of slope lowers because seismic force of the approximate 3D is larger than the case with 2D as shown so far. As for the influence that the seismic response in a valley transverse cross-sectional direction in the condition of 100gal gives the slope stability as an incident amplitude of 1Hz sine wave half wavelength in addition to the condition in the assumption of linear of the valley fill ground, it can be seen, the safety factor decreases by about several percent or less. It has been understood that it is important to consider not only the strength of a ground but also the influence of geographical features in a valley transverse cross-sectional direction expect it appropriately when thinking about the effect of three dimensions in the stability analysis on the valley fill.

4. APPLICATION TO FILLING SLOPE FAILURE BY NOTO HANTO EARTHQUAKE

4.1. Outline of the Earthquake and Slope Failure Site of Noto Tollway

The Noto Hanto Earthquake of magnitude M=6.9 of the hypocenter in the Ishikawa Prefecture Noto peninsula offing was struck at 9:42 March 25, 2007. The hypocenter depth was 11km. Many slope failures were occurred, a lot of houses were collapsed, and traffic was intercepted by this earthquake. The one of large-scale fill failure was occurred by this earthquake in the Ishikawa prefectural highway road public corporation Noto tollway. The width (W) of this valley is about 60m, and the thickness of the fill of the valley (D) is 15-20m, and W/D is roughly equal to 3. The bed-rock is an andesite quality tuff according to the bore data after the earthquake, and the fill is composed of the gravel mixing cohesive soil. Average N value is roughly 7.



Geotechnical parameters

	Vs m/s	N	ρ kN/m³	ν	c kN/m²	ϕ (°)	G,h~γ type
①Layer	190	6.7	17.6	0.45	15	30	Non-linear
②Layer	475	66	21.6	0.45	–	–	Linear

Figure 6. Slope Failure Site of Noto tollway. Left panel: The slope failure that had happened by the Noto Hanto Earthquake in 2007. Right panel: 2D models for valley axis direction of fill slope.

The inclination of the direction of the bed-rock of the valley axis is about 18.5°and the fill inclination is about 26.5°as shown in Figure-6(right panel). The resident in the vicinity witnessed failure of this fill slope immediately after the earthquake. Therefore we guessed that the factor of this slope failure was the seismic ground motion because we heard this person's information.

4.2. Simulation of Input Earthquake Motion for In-situ Analysis

The strong motion records were observed with the Japanese nationwide strong-motion network, KiK-net (2007), in the Noto Hanto Earthquake. Surface of the ground and underground strong motion records were obtained in 11 points near this slope failure shown in Figure-7(left panel). The incident seismic ground motion used for this study was calculated by the asperity distribution that Kuse et al.

(2008) had presumed. Concretely, inversion for the presumption of the asperity distribution was executed because of the seismic wave technological and considerable base (Vs=500m/s) converted by using frequency dependence type ground shake analysis method (FDEL code) for the ground model made by the bore data of 11 places. In addition, the waveform synthesis was done by using presumed asperity distribution, and using seismic ground motion forecast method (EMPR code) that Sugito et al.(2000) had developed. Input incident wave is shown in Figure-7(right panel). We adopted 130gal in the verification analysis as twice the rock-outcrop incident acceleration wave.

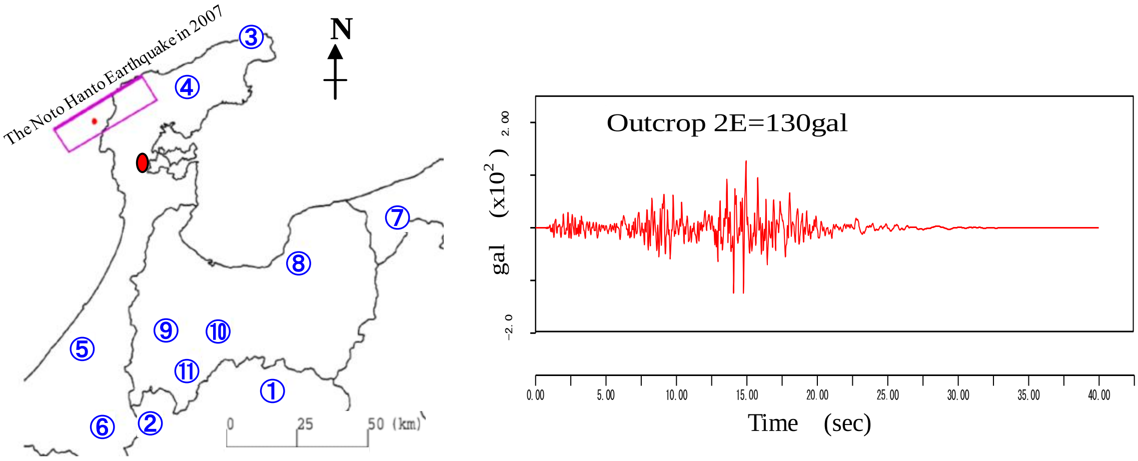


Figure 7. The study point (red point), hypocenter ,and 11 strong motion record points (left panel). Input incident wave (right panel)

4.3. Verification Analysis Model and Analytical Result

The valley axis sectional model is shown in Figure-6(right panel) as a valley fill model by two dimension finite element analysis (FLUSH code). The energy transmission boundaries were set to the both sides as a boundary condition, and the viscous boundary was set in the bottom. The shear velocity of the valley fill ground (① layer) and the base (② layer) are assumed to be Vs_1=190m/s and Vs_2=475m/s as shown in Figure-6(right panel). As the ground physical properties, it is assumed γ_1=17.6kN/m^3 and γ_2=21 .6kN/m^3. The nonlinearity of the fill ground applied G,h-γ type of the clay as general in Japan by Fujikawa et al.(2006). A valley transverse cross-sectional model was assumed to be W/D=3 (W=45m, D=15m) and θ=45°.

As a result, the acceleration amplification in the valley axis section is shown in Figure-8 (left panel). The acceleration has been amplified in the fill top as pointed out. The acceleration amplification is 303gal. Figure-8(right panel) is plotting of the ratio between the amplitude of incident acceleration (2E=130gal) and the amplitude of the ground surface acceleration in a valley transverse cross-sectional direction. The acceleration in the valley transverse cross-section is amplified gradually in the center part of the valley fill as well as the result of the case study in 1Hz sine wave half wavelength. The extra coefficient β compared with the amplification of horizontal stratification and the amplification by geometry effect is about 1.35 as shown in figure-8 (right panel).

4.4. Stability Analysis

The geotechnical parameters of the ground model obtained c=15kN/m^2 and φ=30° from triaxial-compression test (CU, unsaturated) as 90% compaction degree (ρ_d=90%) according to a local banking material. The groundwater level was considered the upper surface of the base-rock layer. The stability analysis used the two dimension circular arc Fellenius method.

Equation 4.1 is considered as coefficient *Kh* of the seismic force used for the stable computation in the direction of the valley axis. The extra surcharge coefficient β of geometrical amplification by the inclination of the base in a valley transverse cross-sectional direction is considered in this study. Figure-8 shows that the value of β is equal to 1.35.

$$Kh = \alpha \cdot Amax(SV)/g \cdot \beta = 0.7 \cdot (303/980) \cdot 1.35 = 0.30 \qquad (4.1)$$

Here, Amax (SV) is an amplification acceleration of the slope in the valley axis direction, and β is an extra coefficient of the amplification of a valley transverse cross-sectional direction. α is mean value of the acceleration in the direction of the fill depth to the maximum value of the acceleration.

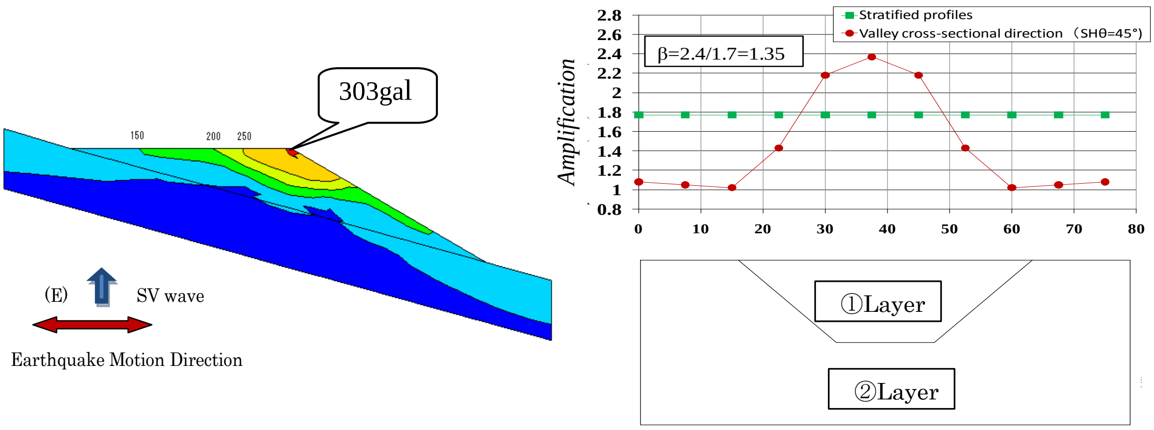


Figure 8. The surface acceleration in a valley axis direction (left panel). The extra coefficient β compared with the horizontal stratification and the valley transverse cross-sectional direction (right panel)

Table-1 shows the results of the stability analysis. The safety factor without considering seismic force was Fs=1.54 (*Kh*=0.0), and that with considering seismic force in the direction of the valley axis was Fs=1.07 (*Kh*=0.22). Therefore, it could not simulate the failure of the fill slope in this study point. On the other hand, it was given the seismic force (*Kh*=0.30) as well as the amplification surcharge of β by irregularly of base-rock in a valley transverse cross-sectional direction. The safety factor with considering β was Fs=0.96 (*Kh*=0.30). It agreed to the result of the failure of this fill slope by the simulation. However, a lot of causes and factors exist besides the factor by this research. As the example, groundwater level influences, excess pore water pressure influences, the influence of a long-term deterioration in strength of the ground, shear-strain dependency of soil, vertical earthquake motion, so on.

Table 1. The Stability Calculation Result of Considering Bounding Irregularly of The Base in The Valley Axis and The Valley Transverse Cross-sectional Direction.

	Kh	***Fs***	***Actual phenomenon***
Not consider of seismic force (Valley axis direction)	***0.0***	***1.54***	***Not failure (agree)***
Consider of seismic force (Valley axis direction)	***0.22***	***1.07***	***Failure (not agree)***
Consider of seismic force of geometry effect (Valley transverse cross-sectional direction)	***0.30***	***0.96***	***Failure (agree)***

As for the influence of geometrical amplification of the seismic ground motion by the inclination of the base-rock formation in a valley transverse cross-sectional direction, it has been understood that there is a possibility of greatly influencing the stability of the fill (decrease at the safety factor) as well as other factors.

5. RESEARCH OF PREVENTION COUNTERMEASURE IN FILLING VALLEY

5.1. Concept of Seismic Ground Motion Control

The main current of the countermeasure for slope stability is how to increase strength of the fill. There are few studies of a prevention countermeasure for slope stability that controls the acceleration. The amplification of the seismic response in the ground on the inclination base-rock is refraction and a reflection of the seismic wave that passes the shape of complex base formation. The amplification of the seismic wave is caused by overlapping with the wave refraction in addition to the wave that transmits below. If basic shape is simple, we can analyze not only the maximum value of the seismic ground motion but also the position in which the maximal acceleration is generated. It is said that V character type and U character type of basic shape of filling valley are general. As the concept, coefficient (Fk) for shape complexity of base-formation was considered for countermeasure.

Fk=0　1 layer ground　*f(fz)*
Fk=1　horizontal stratification (two layer ground)　*f(fz,Ip)*
Fk=2　one side of base inclination (two layers and inclinations)　*f(fz,Ip, θ)*
Fk=3　both sides of base inclination (two layers and both sides inclinations)　*f(fz,2(Ip),2(θ))*
・・
Fk=n　n place basic inclination (n layer and n inclination)　*f(fz,n(Ip),n(θ))*

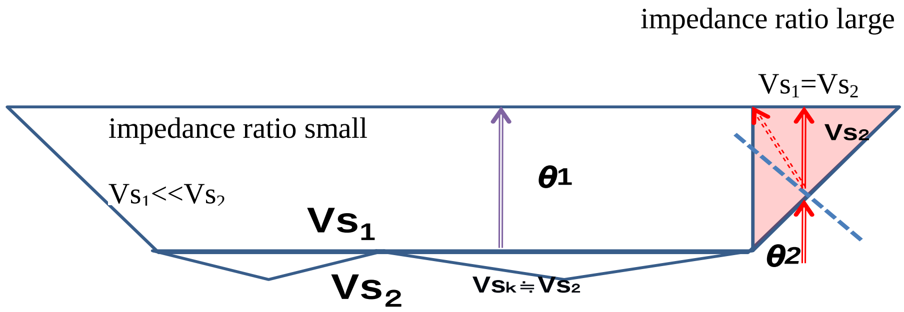


Figure 9. Coefficient (Fk) for shape complexity of base-formation

Seismic ground motion becomes complex by overlapping the reflection and refraction as the value of Fk increases. The damage of the frame house and the civil structure occurs because of the seismic ground motion of the frequency band of about 0.1Hz-5Hz. If the wavelength of the seismic ground motion in the fill of V=100-200m/s is calculated, it becomes about 20-2000m. Because this wavelength contains width and the depth of the valley, the shape of a valley that is smaller than this wavelength hardly influences the amplification of the seismic ground motion. In the present study, it is considered about the valley of the size of 100m order. Because of the large scale wavelength, the countermeasure that satisfies complex coefficient Fk infinite (∞) is unreal. On the other hand, the maximum value and the location of occurrence of overlapping the seismic ground motion at about Fk=2 can be easily presumed shown in Figure-9. Therefore, if Fk can be brought close to one, the seismic ground motion becomes near one dimension earthquake response of the horizontal stratification ground. In the present study, the method of making Fk infinity was given up, and the method of bringing Fk close to 0 was selected. Therefore, refraction and overlapping are controlled by increasing the impedance ratio by the method of constructing the shear velocity of the banking material on the inclination base as well as the base-rock formation(Vs1=Vsb). The reflection of horizontal direction at the edge is suppressed by using the material with the effect of damping.

5.2. Evaluation of Countermeasure for Filling Slope Failure by This Technique

The effect of this concept of the countermeasure was evaluated with slope failure site of Noto Tollway of Figure 6. The extra coefficient β of filling valley without the prevention countermeasure is 1.35. Coefficient Kh of the seismic force is 0.3. (Kh= $\alpha \cdot$A max(SV) / g$\cdot$ β =0.22$\cdot$1.35 = 0.30) .The safety factor Fs is 0.96. The method of vertically planning the upper part of the inclination base by macadam was tried shown in Figure 10. β in case that improves the banking material to Vs=475m/s is 1.01. Therefore, Kh becomes 0.22. (Kh= $\alpha \cdot$A max(SV) / g$\cdot$ β = 0.22$\cdot$1.01 = 0.22) Safety factor for slope stability Fs increased to Fs=1.07 shown in table-2. Here, the damping effect of macadam is not considered. When the shear wave velocity of the countermeasure part of the fill ground was made the same velocity as the base-rock formation, the decrease of the seismic ground motion became about 50% compared with without countermeasure show in Figure 11. The effect of the countermeasure for slope stability during earthquake was confirmed by using this technique of concept.

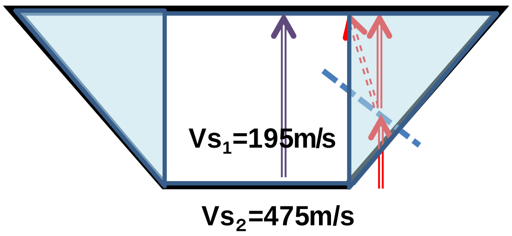


Figure 10. The method of vertically planning the upper part of the inclination base by macadam

Table 2. The Stability Calculation Result of The Valley Transverse Cross-sectional Direction.

	extra coefficient *β*	*Coefficient Kh*	*safety factor* *Fs*
Not consider of countermeasure (Valley transverse cross-sectional direction)	*1.35*	*0.30*	*0.96*
Consider of countermeasure (Valley transverse cross-sectional direction)	*1.01*	*0.22*	*1.07 (Effective)*

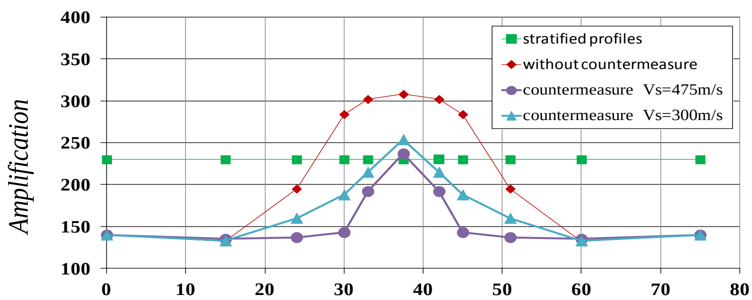


Figure 11. The effect of decrease at the seismic ground motion by countermeasure or not

6.CONCLUSION

The conclusion obtained in the present study is shown below:

1) The authors discussed, with 2-D FEM analysis, the effects of the transverse cross-sectional geometry of the valleys on the slope stability during earthquakes.

2) The study shows that the amplification of the acceleration during earthquakes is greatly related to valley width (W), valley depth (D).It has been understood that the acceleration amplifies with roughly W/D=5 greatly influenced by the focusing effect and overlapping wave motion in a valley transverse cross-sectional direction.

3) Slope stability of the valley fill depends not only on the earthquake motion response in the valley axis direction but also on the amplification of the motion associated with the transverse cross-sectional shape of the valley. In evaluating slope stability, two components of the vibrations were considered and superimposed; the first was the earthquake vibration in the direction of the valley axis without considering the geometry effects, and the second was vibration that induced by the cross-sectional shape of the valley.

4) This technique was applied to the slope failure that occurred at the filled valley along the Noto toll road during the Noto Hanto Earthquake in 2007.The study shows that while the factor of safety of the slope without considering the geometry effects was above unity, it was below unity with consideration of the geometry effects, with several percent of reduction in the factor of safety.

5) The example demonstrates the effectiveness of the proposed method and illustrates necessity to adequately include the effect of the valley geometry in the stability evaluation.

6) As the concept, coefficient (Fk) for shape complexity of base-formation was considered for countermeasure. Refraction and overlapping are controlled by increasing the impedance ratio by the method of constructing the shear velocity of the banking material on the inclination base as well as the base. (Vs1=Vsb)

8) The method of vertically planning the upper part of the inclination base by macadam was tried. The effect of the countermeasure for slope stability during earthquake was confirmed by using this technique of concept.

AKCNOWLEDGEMENT

The authors would like to thank Dr. Kuse (Gifu University) for the data reduction of the strong motion record. The strong motion records obtained by K-NET and KiK-net were used in this study.

REFERENCES

Kamalian, M., Jafari, M.K., Sohrabi-Bidar. and Razmkhah, A. (2008). Seismic Response of 2-D Semi-sine Shaped Hills to Vertically Propagating Incident Waves. *Earthquake Spectra.* **Volume 24: No.2**, 405-430.

Assimaki,D.,Kausel,E. and Gazetas,G. (2005). Soil-Dependent Topographic Effects. *Earthquake Spectra.* **Volume 21: No.4**, 929-966.

Kuse,M., Sugito,M. and Nojima,N. (2008). Prompt Estimation of Strong Ground Motion Near Focal Region Based on Fault Inversion from Acceleration Records. *14th World Conference on Earthquake Engineering*. Paper No.03-01-0052.(CD-ROM).

Aoi,S., and Sekiguchi,H.(2007). Source Process of the Noto Hanto Earthquake Derived from Near-fault Strong Motion Data. http://www.k-net.bosai.go.jp/k-net/topics/noto07325/ (in Japanese)

Sugito,M., Furumoto,Y. and Sugiyama,T. (2000). Strong Motion Prediction on Rock Surface by Superposed Evolutionary Spectra. *12th World Conference on Earthquake Engineering*. Paper No.2111.(CD-ROM).

Fujikawa.S.,Senna.S.,Fujiwara.H.and Ooi.M.(2006).Earthquake Motion Amplification of Surface Soil Layeres at the Strong Motion in Ojiya during the 2004 Mid Niigata Earthquake. J*ournal of Japan Association for Earthquake Engineering*.**Vol.6: No.3**,27-41.