Research Article

Effects of Earthquake on Behavior Characteristics of Fault Gouge in Time-History Analysis of Slope

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A time-history analysis, based on the finite element method, was performed to identify the behavior of a slope containing fault gouge during earthquakes. Input seismic waves were obtained from earthquake data measured in Korea, with five earthquakes (M3.0, M3.9, M5.1, M5.4, and M5.8) to analyse the magnitude effects. The acceleration effects indicate approximately 50%–110% residual shear strain depending on the acceleration fluctuation within the coda wave section after the maximum acceleration was reached. This indicates that the permanent deformation due to the earthquake will remain because the ground is an elastic-plastic material. The magnitude effects also indicate that both the maximum shear stress and strain increase simultaneously as the magnitude increases and as the maximum acceleration tends to increase with increasing magnitude. However, both the cumulative and maximum accelerations should be considered when assessing slope stability since both the maximum shear stress and strain are affected by these two accelerations. Analysis of the presence or absence of fault gouge indicates that the shear strain could be concentrated on fault gouge, which is easily deformed or destroyed by shear strain.

1. Introduction

The fault core accommodates intense deformation in a fault zone via crushing, weathering, and/or alteration, and possesses a low strength compared with the surrounding host rock [1–4]. The low strength of the fault core is due to the very weak materials of which it is composed, such as fault gouge, with an increase in fault gouge content leading to a severe decrease in the strength of the fault rock [5–9]. This weak fault gouge shapes the role of the fault core in various surface instabilities, such as slope failure, differential erosion, and soil loss. Numerous studies have attempted to clearly identify the physical and mechanical characteristics of fault cores; however, most studies have focused on the static behavior of fault gouge, such as its permeability, uniaxial strength, deformation modulus, friction angle, and cohesion [10, 11], instead of the dynamic behavior of fault gouge, such as its stress and strain during earthquakes.

Previous dynamic slope analysis studies can be classified into three categories: a comparison of the results obtained from various dynamic analysis methods, including pseudostatic analysis, the permanent displacement method, and time-history analysis, under the same conditions; slope stability analyses that incorporate a time-history analysis and the strength reduction method during an earthquake; and identification of the ground response during an earthquake. An example comparative study of pseudostatic and time-history analyses for rock slopes in the Indian Himalayas that was conducted by Latha and Garage [12] reported that pseudostatic analyses, which consider only peak ground acceleration (PGA), can produce incorrect results. Furthermore, Reddy and Krishna [13] analysed the
dynamic slope response for three earthquake scenarios and concluded that the slope was unstable via the pseudostatic analysis, whereas the vertical and horizontal displacements were within allowable ranges because of attenuation based on the amplitude, frequency, and duration of the earthquakes via the time-history analysis. Numerous similar studies have insisted that time-history analyses provide more realistic results than other dynamic analysis methods [14, 15]. The second category of studies has focused on evaluating slope stabilities using time-history analysis and the strength reduction method during an earthquake [16, 17]. Islam et al. [18] performed time-history analysis for a sensitive clay slope and analysed the relationships between the observed landslides and their runouts based on the slope angle and clay mineral composition. They reported that the slope geometry affected the run-out length, with the sensitive clay layer promoting spread-type failure in the toe of the landslide. The third category of dynamic slope stability studies has focused on the ground response. Cong et al. [19] explored the boundary effects on the seismic response of a three-dimensional (3D) slope and concluded that an increase in the PGAs of earthquake events tends to enlarge the difference among the three lateral boundaries, whereas the differences between the three lateral boundaries are small for an earthquake with a larger predominant period. Moscatelli et al. [20] studied the effect of stratigraphy and geotechnical properties on the seismic response in an explosive volcanic setting and reported that the occurrence of alternating soft and stiff materials in the central part of the maar strongly increases the site amplifications occurring at the surface.

Previous dynamic slope analysis studies have only concentrated on either comparison of different dynamic analysis methods, assessments of the safety factor, or the identification of acceleration response changes based on the ground materials, and there are few studies conducting time-history analyses of slopes containing fault zones to investigate the effects of stress/strain changes, fault zone behavior, and other factors on slope stability. However, difficulties can arise when large-scale fault zones are encountered because civil engineering works, such as tunnels, bridges, and power plants, are becoming increasingly larger, longer, and/or more complex. Thus, ground deformation studies that investigate fault zone behavior during an earthquake can therefore be applied to mitigate or prevent earthquake-induced damage.

Here, we perform 3D modelling along a slope containing fault gouge by inputting the physical and mechanical properties, such as unit weight, friction angle, cohesion, dynamic elastic modulus, and dynamic Poisson’s ratio, obtained from a series of laboratory and in situ tests to conduct a time-history analysis. The seismic waveforms for the time-history analysis consist of acceleration data obtained in Korea, with seismic waveforms from M3.0, M3.9, M5.1, M5.4, and M5.8 events used to analyse the slope stability for different earthquake magnitudes. We then analyse the effects of seismic acceleration and fault gouge behavior on slope stability using the time-history analysis results.

2. Modelling and Input Parameters

2.1. Slope Modelling for the Time-History Analysis. The 3D finite element method analysis in this study was conducted using MIDAS GTS/NX, which was developed for geotechnical engineering [21]. There are many dynamic analysis research studies using MIDAS GTS/NX. For example, Mohammed [22] and Ryu et al. [23] analysed the behavior of underground structures such as storage caverns and tunnels when blasting for excavation led to vibration near ground. Also, Cao and Hang [24] analysed the settlement of soft clay ground by simulating the vibration of subway, and Al-Jeznawi et al. [25] studied the behavior of soil-pile interaction under the effect of coupled static-dynamic loads. Like aforementioned, MIDAS GTS/NX program is applied to a lot of engineering fields because it has powerful processing functions, which can meet engineering needs. However, there are no cases of dynamic analysis that use this program for slope including fault zones.

The isotropic characteristics of the ground material were assumed, and the Mohr–Coulomb destruction criteria were applied to simulate the elastic-plastic behavior of the ground. The base and lateral side of the slope were set as viscous boundaries in MIDAS [21], whereas the base and lateral side of the slope were set as viscous and free-field boundaries, respectively, in FLAC [26].

The selected slope for the slope stability analysis was located in the Bonggil-ri area of Gyeongju-si, which consists of an approximately 240-m-long by 60-m-high section. A geological survey of the slope has indicated that the slope consists primarily of Cretaceous sedimentary rocks, with some more recent igneous intrusions. A number of faults were also observed within the slope, with some sections near the fault zone containing soil and clay owing to extensive weathering and alteration. In accordance with the international criterion of weathering grade [27], the weathering grade of the slope indicated that most of the rocks were highly weathered (H.W.) to moderately weathered (M.W.) across the slope (Figure 1).

The slope was classified as M.W. and H.W. sedimentary rock and soil, with the material at the base of the slope classified as S.W. sedimentary rock (Figure 2). Furthermore, only the six fault gouges that were greater than 1 m wide were considered in the modelling, numbered 1 to 6 from left to right in Figure 2. The host rock types, widths, and orientations for each fault gouge are given in Table 1.

The mesh size for slope modelling is calculated using the following equation, with the mesh sizes of the fault gouge and other areas, which contain soil and rocks, set at 1 and 5 m, respectively, based on a slope height of ~60 m [28]:

\[
l \leq \frac{\lambda}{10}, \quad f \leq \frac{v_s}{10 \times l},
\]  

where \(l\) is the maximum length of mesh, \(\lambda\) is the wave length, \(f\) is the frequency, and \(v_s\) is the velocity of shear wave.

2.2. Physical and Mechanical Properties. The general ranges for the physical and mechanical properties of the soil and
The physical and mechanical properties of the soil layer are based on the average of 392 data observations obtained from 39 construction projects in Korea, and the static properties of the rock, such as its unit weight, friction angle, and cohesion, are based on the average of 4,280 data observations obtained from 107 construction projects in Korea. Furthermore, the dynamic properties of the rock, such as its dynamic elastic modulus and dynamic Poisson’s ratio, are based on 2,210 data observations obtained from 60 construction projects in Korea. Here, most friction angle and cohesion were obtained from a triaxial compressive test, and most dynamic elastic moduli and dynamic Poisson’s ratio were measured from a downhole test. If P- and S-wave velocities for each rock quality are measured from downhole tests at boreholes, the dynamic elastic modulus and the dynamic Poisson’s ratio can be calculated using the following equations, respectively:

\[ E_d = \frac{\rho V_p^2 (3V_p^2 - 4V_s^2)}{(V_p^2 - V_s^2)} \]  

\[ v_d = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \]
where $V_P$ is P-wave velocity (m/s), $V_S$ is S-wave velocity (m/s), $\rho$ is the unit weight (or density; g/cm$^3$), $E_d$ is the dynamic elastic modulus (MPa), and $\nu_d$ is the dynamic Poisson’s ratio.

However, the ranges of the fault gouge properties are large because of their heterogeneity, with few studies constraining the dynamic characteristics of fault gouge. Therefore, the physical and mechanical properties of the fault gouge are obtained via a series of laboratory tests, such as water content [32], specific gravity [33], direct shear [34], and in situ tests, such as a three-component seismic survey on a sample collected from a large-scale fault zone near the site [35]. The physical and mechanical properties of the different rock types comprising the ground mass (soil, rock mass, and fault gouge) are shown in Table 2; these values were applied during the time-history analysis of the slope. The mass and stiffness proportionality coefficients ($\alpha$ and $\beta$, respectively) have been calculated via an eigenvalue analysis, with a Rayleigh damping ratio of 5% assumed.

### Table 2: Applied physical and mechanical properties for the time-history analysis of each rock type. The slope consists of soil and fault gouge that originated from granite and sedimentary rock, and slightly weathered (S.W.), moderately weathered (M.W.), and highly weathered (H.W.) sedimentary rocks.

| Rock type     | Soil   | Unit weight (kN/m$^3$) | Cohesion (kPa) | Friction angle (°) | Dynamic elastic modulus (MPa) | Dynamic Poisson’s ratio |
|---------------|--------|------------------------|----------------|-------------------|-------------------------------|-------------------------|
| Granite       | Fault  | 18.0                   | 15             | 27.8              | 1,073                         | 0.269                   |
| Sedimentary rock | S.W. | 26.0                   | 10,830         | 55.4              | 27,400                        | 0.322                   |
|               | M.W.  | 24.6                   | 11,250         | 53.0              | 18,618                        | 0.336                   |
|               | H.W.  | 21.0                   | 9,000          | 54.5              | 1,650                         | 0.471                   |
|               | Fault g. | 19.6                   | 11             | 27.7              | 1,452                         | 0.269                   |

### Table 3: Earthquake information for the five earthquakes used in the time-history analysis.

| Magnitude | Location   | Distance (km) | Relative PGA time (s) | PGA (m/s²) |
|-----------|------------|---------------|-----------------------|------------|
| M5.8      | Gyeongju-si | 12            | 2                     | 3.30       |
| M5.4      | Pohang-si  | 11            | 4                     | 2.66       |
| M5.1      | Gyeongju-si | 12            | 3                     | 2.45       |
| M3.9      | Iksan-si   | 29            | 3                     | 1.28       |
| M3.0      | Gyeongju-si | 14            | 4                     | 0.27       |

Twenty-second seismic waveforms were used for the time-history analysis. The PGA occurred within 2–4 s of the first arrival, and the amplitude fluctuations in the seismic waveform largely decayed to background noise levels within 7 s of the PGA (amplitude fluctuations generally less than 5% of the PGA). The time increment is generally in the 0.02–0.1 s range during time-history analyses; however, it was difficult to assess the effect of seismic acceleration on the analysed seismic waveforms because there were many fluctuations within these time increments. Therefore, 0.5-s intervals were used for the time-history analysis of the seismic waveforms, with the analysis results derived over 40 time steps for each earthquake.

2.4. Analysis Points in the Model. The analysis points are selected throughout each rock type across the slope, which includes soil, and H.W. and M.W. sedimentary rocks, as well as 2–4 points in each fault gouge, depending on the persistence of a given fault gouge in the slope (Figure 4), to identify the behavior of a slope containing fault gouge during an earthquake. The shear stress and strain are largely concentrated on the fault gouges, as well as the soil near some of the fault gouges, such that the data used in the analysis are the shear stress and strain measurements at each point.

The time-history analysis data were derived by applying the seismic acceleration in the x-axis direction, which is the dip direction of the slope. The seismic acceleration can be applied in the x-axis (dip direction of the slope), y-axis (strike direction of the slope), and z-axis (vertical direction of the ground surface) directions, with the maximum acceleration, maximum velocity, and maximum displacement shown in the same direction as the applied seismic acceleration direction. Furthermore, acceleration, velocity, and displacement possess a differential or integral relationship, and follow a similar trend. Therefore, we did not consider the acceleration, velocity, and displacement at each point, and...
the shear stress and strain from applying the seismic acceleration in X-direction, which is the most unstable direction in terms of slope safety, are analysed. Also, an analysis of the safety factor was not conducted because the fault gouges do not play a role in the evolution of the failure surface.

3. The Analysis on Seismic Acceleration Effects

The shear stress and strain patterns were analysed at each fault to identify the slope behavior for a given applied seismic acceleration. The seismic acceleration-shear stress and seismic acceleration-shear strain results for the five earthquakes (M3.0–M5.8) are shown in Figure 5, where both the maximum shear stress and strain occur at the PGA time, with the exception of the M3.9 earthquake. The maximum shear stress and strain appear to be delayed by 0.5s relative to the PGA time for the M3.9 earthquake, which may be due to the fact that this delay causes the acceleration to be applied in the same direction as the PGA immediately after the PGA for the seismic waveform of the M3.9 earthquake.
Figure 4: Distribution of the analysis points (yellow circles) in the slope, which span the various materials throughout the slope (soil, fault gouge in granite and sedimentary rock, and H.W. and M.W. sedimentary rock).

Figure 5: Continued.
(c) 

(d) 

(e) 

(f) 

Figure 5: Continued.
Figure 5: Correlations between the time history, and shear stress and strain for each earthquake. (a) and (b) M3.0, (c) and (d) M3.9, (e) and (f) M5.1, (g) and (h) M5.4, and (i) and (j) M5.8. (a) Shear stress due to the M3.0 earthquake. (b) Shear strain due to the M3.0 earthquake. (c) Shear stress due to the M3.9 earthquake. (d) Shear strain due to the M3.9 earthquake. (e) Shear stress due to the M5.1 earthquake. (f) Shear strain due to the M5.1 earthquake. (g) Shear stress due to the M5.4 earthquake. (h) Shear strain due to the M5.4 earthquake. (i) Shear stress due to the M5.8 earthquake. (j) Shear strain due to the M5.8 earthquake.
Figure 6: Continued.
(Figures 5(c) and 5(d)). Furthermore, the changes in seismic acceleration are similar to the changes in shear stress and strain for each of the earthquakes since the seismic attenuation effects (increase or reduction) are directly reflected in the shear stress and strain.

The shear stress and strain at PGA were compared with the shear stress and strain at the average acceleration of the Coda wave section (10–20 s) for each fault gouge. The Coda wave section is the latter part of the seismic waveform after the arrival of the major waves, such as the P, S, and surface waves [37]. In this study, it is defined as the 10–20 s section in each waveform, which is when the amplitude fluctuations in the seismic waveform converge after the PGA. The maximum shear stress and strain appear when the PGA is applied, and the residual shear stress and strain appear when the Coda wave is applied. Here, the residual-to-peak (R/P) ratio is used to categorise the behavior of each fault gouge.

The R/P ratio for each fault gouge due to a M5.8 earthquake is shown in Figure 6, where the shear stress and strain R/P ratios are approximately 50%–55%. The R/P ratios for each of the modelled earthquakes are summarised in Table 4.

The R/P ratio analysis results of the fault gouge for each modelled earthquake show that the R/P ratio is approximately 40%–55% for each earthquake, except for the M3.9 earthquake, which means that approximately half of the maximum shear strain remains in the fault gouge after the earthquake. This observation suggests that permanent deformation has occurred. Here, permanent deformation due to stress is explained for the case of soil. The strain in the soils moves from point A to point B along the stress-strain curve in Figure 7 when the soils are stressed (loading) below the point of shear failure. The strain in the soils then moves from point B to point C along the stress-strain curve when the stress is removed (unloading). The strain is not restored to its

**Figure 6**: (a) Shear stress and (b) shear strain due to the M5.8 earthquake in the six fault gouges, which show that the residual-to-peak ratio is approximately 50%–55% for each fault gouge.
original state (point A in Figure 7), but is rather restored to a state with permanent strain (point C in Figure 7) [38, 39]. The R/P ratio is approximately 110%–115% for the M3.9 earthquake (Table 4). The seismic acceleration data for the modelled earthquakes were scaled to the seismic acceleration of the M5.8 earthquake to identify the cause of the variation in the R/P ratio among the modelled earthquakes (Figure 8(a)). The Coda wave section (10–20 s), which is when the seismic amplitudes converge to zero, highlights that only the seismic waveforms for the M3.9 (red line) and M5.8 (blue line) earthquakes have notable amplitude fluctuations (Figure 8(b)). However, the M3.9 earthquake has an R/P ratio of approximately 110%, whereas the M5.8 earthquake has an R/P ratio of approximately 50%. These differences are considered to be closely related to the acceleration direction. The seismic waveform for the M3.9 earthquake has mostly positive (+) accelerations, whereas the seismic waveform for the M5.8 earthquake has alternating positive (+) and negative (−) accelerations, which attenuate and/or create an offset in the data. Therefore, the seismic waveform for the M5.8 earthquake has accelerations in different directions that reduce the effect on the residual shear stress and strain. These results indicate that both the PGA and acceleration of the Coda wave section should be considered in the time-history analysis because the permanent strain due to the Coda wave could be larger than that of the PGA.

4. The Analysis on Earthquake Magnitude Effects

The maximum shear stress and strain were analysed at all of the fault gouges to identify the earthquake magnitude effects. The distribution of the PGA and maximum shear stress (or strain) for each earthquake magnitude are shown in Figure 9. Both the maximum shear stress and strain tend to increase as the magnitude increases in the granite and sedimentary rock fault gouges, except for the M5.4 earthquake. The PGAs are 0.27, 1.28, 2.45, 2.66, and 3.30 m/s² for the M3.0, M3.9, M5.1, M5.4, and M5.8 earthquakes, respectively, but the maximum shear stress and strain for the M5.4 earthquake are lower than those for the M5.1 earthquake (the red box in Figure 9). This trend appears to be the same in all of the fault gouges, suggesting that factors other than the attitude of the fault gouge zone or PGA caused this deviation.

The seismic acceleration data for the M5.1 and M5.4 earthquakes were compared to identify the cause of these reduced stress and strain values for the M5.4 earthquake. Both seismic waveforms for the M5.1 and M5.4 earthquakes exhibit PGA at 3 s, with the seismic acceleration data for the M5.1 and M5.4 earthquakes having PGAs at 2.45 and 2.66 m/s², respectively (Figure 10). However, the cumulative acceleration (CA) from 0 s until the PGA (3 s) is only 2.13 m/s² for the M5.4 earthquake, whereas it is 3.26 m/s² for the M5.1 earthquake. This reduced CA for the M5.4 earthquake is due to the acceleration just before the PGA, at 2.5 s, being in the opposite direction to the PGA for the M5.4 earthquake, whereas the M5.1 earthquake has an acceleration in the same direction as the PGA, with this variation in the acceleration direction contributing to the lower CA for the M5.4 earthquake.

Further evidence of this CA effect can be seen from the differences between the maximum shear stress for each magnitude, which are similar to the differences between the CA for each magnitude (Figure 11). The CAs are 0.31, 1.25, 3.26, 2.13, and 4.8 m/s² for the M3.0, M3.9, M5.1, M5.4, and M5.8 earthquakes, respectively, and are approximately 4.0, 2.6, 0.7, and 2.3 times as large as the magnitude increases. The maximum shear stress results exhibit a similar trend to the CA results for each magnitude, with differences of approximately 5.5, 1.8, 0.8, and 2.0 times, respectively.
Figure 8: Comparison of the scaled acceleration of the waveforms for the five earthquakes (M3.0, M3.9, M5.1, M5.4, and M5.8). The accelerations of the M3.9 and M5.8 earthquakes are the only ones that exhibit notable amplitude fluctuations in the Coda wave section. However, the R/P ratio for the M3.9 earthquake (red line) is high, at approximately 110%, whereas the R/P ratio for the M5.8 earthquake (blue line) is low, at approximately 50%. (a) Scaled acceleration for each earthquake. (b) Scaled acceleration within the Coda wave section for each earthquake.

Figure 9: Continued.
Figure 9: (a) Maximum shear stress and (b) maximum shear strain of the six fault gouges for each earthquake magnitude. The maximum shear stress and strain increase as the magnitude increases. However, both the maximum shear stress and strain for the M5.4 earthquake are lower than those for the M5.1 earthquake.

Figure 10: Acceleration graphs for the M5.1 and M5.4 earthquakes. The maximum acceleration of the M5.4 earthquake is higher than that of the M5.1 earthquake. However, the cumulative acceleration of the M5.4 earthquake is lower than that of the M5.1 earthquake due to acceleration being in the opposite direction just before the PGA.
Therefore, it is considered that the maximum shear stress and strain are significantly affected by both the CA and PGA.

The abovementioned results were verified by comparing the results of a pseudostatic analysis, which only reflects the PGA, with those of the time-history analysis, which reflects the seismic acceleration over time. A comparison of the maximum shear stress and strain for each earthquake magnitude and fault gouge nos. 1–6 is shown in Figure 12. The pseudostatic analysis results show that the maximum shear stress and strain increase as the earthquake magnitude increases, whereas the time-history analysis results show that the maximum shear stress and strain for the M5.4 earthquake are lower than those for the M5.1 earthquake, depending on the CA effect. Therefore, the time-history analysis is considered to be a more realistic analysis method than the pseudostatic analysis.

5. The Analysis on Effects of the Presence or Absence of Fault Gouge

The time-history analysis results, which are based on the respective mechanical properties of fault gouge and H.W. rock, are compared to identify the slope behavior in either the presence or absence of fault gouge. The results for fault gouge in sedimentary rock (fault gouge 2, 4, and 5) during
the M3.0 and M5.8 earthquakes are shown in Figure 13, with the mechanical properties of fault gouge being similar to those of H.W. rock. The results for fault gouge in granite (fault gouge 1, 3, and 6) during the M3.0 and M5.8 earthquakes are shown in Figure 14, with the maximum shear stresses due to the mechanical properties of H.W. rock being larger than those of fault gouge. However, the maximum shear strain appears to be concentrated in fault gouge and is approximately 1.2–2 times larger than the applied mechanical properties of H.W. rock.

Both the shear stress and shear strain are affected by the shear modulus:

$$\tau = G_d \times \epsilon_{\text{shear}}$$  
(4)

where $\tau$ = shear strength, $G_d$ = dynamic shear modulus, and $\epsilon_{\text{shear}}$ = shear strain.

(4) shows that the shear strain may increase or decrease depending on the dynamic shear modulus of the materials when the same shear stress is applied. The dynamic shear moduli of fault gouge and H.W. rock in granite and sedimentary rock are calculated using the dynamic characteristics in Chapter 2.2, with the results presented in Table 5. The maximum shear stress in sedimentary rock exhibits a similar tendency to the maximum shear strain because the dynamic shear modulus of fault gouge is similar to that of H.W. rock. However, the large differences in the dynamic shear moduli of granite yield a large shear stress in H.W. rock and a large shear strain in fault gouge.

The dynamic characteristics of fault gouge indicate that the dynamic shear modulus of fault gouge is most likely to be lower than that of the surrounding rock (H.W. rock—fresh rock) because the P- and S-wave velocities of fault gouge are lower than those of the surrounding rocks. This low dynamic shear modulus can cause a large displacement or shear failure during an earthquake because the shear strain is concentrated in the fault gouge. Furthermore, fault gouge can be classified as H.W. rock because fault gouge exists between rock and rock, and often has a texture, such as foliation. However, the time-history analysis results highlight that it is necessary to clearly recognize the fault gouge and incorporate its characteristics into the analysis since H.W. rock and fault gouge possess considerably different dynamic shear moduli (Table 5).

6. Discussion

In this section, the results of this study are compared with the results of previous studies, and application and limitation are mentioned. Liu et al. [40] conducted a shaking table test for the two rock slopes, which have a weak layer and the opposite direction, and simulated this situation through 3D dynamic analysis. They observed time lag because the slopes,
which have the opposite directions, were differently applied with positive and negative directions of acceleration. Even Section 3 of this study, it is also confirmed that the time lag can occur depending on the amount of positive and negative acceleration in the seismic acceleration curve since the slope has only one direction (Figures 5(c) and 5(d)), and this result can be considered the same as the results of Liu et al. [40].

In addition, there are some cases that carried out dynamic analysis by embodying the ground containing fault zone [41, 42]. Huang et al. [41] conducted the dynamic analysis for loess-mudstone slope including fault zone and reported that the seismic acceleration of fault zone becomes 1.88 times larger than that of the surrounding rocks. Li et al. [42] conducted dynamic analysis for the tunnel, which passes through fault zone, and observed that the seismic acceleration of the fault zone section is 1.8 times higher than that of the bed rock section. Even in Section 5 of this study, it is also confirmed that the shear stress and shear strain can become from 1.2 times to 2 times larger according to the presence or not of fault gouge. It can be interpreted that this result is the same as the results of Huang et al. [41] and Li et al. [42] because the shear stress and shear strain are proportional to the seismic acceleration of that point. On the other hands, Huang et al. [41] distinguished the surrounding rocks into hanging wall and foot wall based on the fault, and reported that the acceleration of hanging wall is larger than that of foot wall. Although it is difficult to directly compare the results of the hanging wall and foot wall in this study due to multiple faults and various weathering grades, we confirmed the similar results that the shear stress and shear strain at hanging wall are larger than foot wall by comparing points, which have the same weathering grade; 12th (M.W. hanging wall) and 20th (H.W. hanging wall) points of Figure 4 are

![Figure 14: Comparison of the maximum shear stress and shear strain between the fault gouge in granite and H.W. rock due to the (a) M3.0 and (b) M5.8 earthquakes. There is a similar tendency in all of the fault gouges, regardless of magnitude. (a) Maximum shear stress due to the M3.0 earthquake. (b) Maximum shear stress due to the M5.8 earthquake. (c) Maximum shear strain due to the M3.0 earthquake. (d) Maximum shear strain due to the M5.8 earthquake.](image)

Table 5: Dynamic shear modulus of highly weathered rock and fault gouge in granite and sedimentary rock. The dynamic shear moduli of highly weathered rock and fault gouge are similar in sedimentary rock, whereas there is a large difference between the dynamic shear moduli of highly weathered rock and fault gouge in granite.

| Rock type          | Dynamic shear modulus (MPa) |
|--------------------|-----------------------------|
| Granite            | Highly weathered 742 Fault gouge 423 |
| Sedimentary rock   | Highly weathered 561 Fault gouge 572 |

![Table 5](image)
larger than 14th (M.W. foot wall) and 22th (H.W. foot wall) points (Figure 15).

Regarding the topographical characteristics, it was reported not only that the upper part of the slope is more dangerous than the lower part [40] but also that the toe part of the slope is more dangerous because stress and displacement are concentrated [43]. It can be different depending on the distributions of the materials comprising the slope and the influence of adjacent structures. On the slope of this study, the shear stress and shear strain are not particularly concentrated at any of the upper, middle, and lower parts of the slope because various weathering degrees from complete weathering to moderately weathering are complexly mixed.

Until now, a lot of research studies related to earthquake dynamic analysis used the large-scale and well-known overseas earthquakes, such as Chi-Chi earthquake and Tohoku-Oki earthquake. In addition, most studies focused on analysing the difference of waveform and frequency of seismic acceleration for each earthquake or for the stratum. However, this study considered the actual seismic waveform measured in Korea, and it can be practically used in structural analysis by presenting the result as shear stress and shear strain when establishing reinforcement plans such as retaining walls and nails. Since seismic waves are greatly influenced by topographic and geological characteristics, these results will be useful in the geometrical process such as analysing the behavior of slope and/or ground near important structures and establishing reinforcement by considering dynamic conditions of in situ tests. However, verification is limited and very difficult because there is a low possibility of an earthquake occurrence similar to the input seismic waveform in the study area even though it is necessary to verify the results of this study using the data measured in the slope.

7. Conclusions

Time-history analyses were performed on the slope containing fault gouge, with each analysis reflecting the magnitude of five different-sized earthquakes, and the shear stress and shear strain were found to directly reflect the effects of increasing and decreasing seismic acceleration in all of the analytical cases. Furthermore, it was confirmed that the shear strain does not return to its original ground state, with residual shear strain observed, even in the Coda wave sections where the seismic waveform converges after the peak ground acceleration. It is therefore considered that fault gouge experiences permanent deformation, even after the stress is removed, since fault gouge is not a perfectly elastic material. In addition, both the maximum shear stress and strain results for each earthquake magnitude show a tendency to increase with increasing magnitude, but the cumulative acceleration should also be considered since the maximum shear stress and strain are both affected by the cumulative acceleration. The results of time-history analysis show the behavior of fault gouge distributed in the slope during an earthquake, and the permanent deformation and maximum shear strain results were identified based on the seismic waveform history. These results are considered a guide for improving the current criteria for assessing the seismic performance of structures, particularly since only the peak ground acceleration is currently evaluated for structures where seismic performance is important. And then, the analysis results for the presence or absence of fault gouge show that the shear strain can be concentrated in fault gouge with a low dynamic shear modulus in the slope; fault gouge must therefore be considered in the time-history analysis of the slope. Also, our results are verified by comparing the results of previous studies, such as time lag occurred according to the history of the positive and negative directions in the seismic acceleration curve and acceleration, shear stress, and shear strain are larger than the surrounding rocks. In conclusion, it is very important to consider fault gouge for preventing destruction and deformation of slope and ground because fault gouge is inherently unstable due to its heterogeneity and low strength and external forces, such as earthquakes, can cause the shear strain to be concentrated in fault gouge. The results of this study will be able to be practically useful.
for planning the reinforcement design and retaining slope stability in geotechnical engineering field.

Data Availability

The data are available on request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this article.

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