4. Energy approach for earthquake induced slope failure evaluation

Objective:
So far, earthquake-induced slope instability has been evaluated by force-equilibrium of soil mass in engineering practice. An energy approach is proposed here to evaluate slope displacement including large flow deformations. The proposed evaluation method is then applied to many slope failures during 2004 Chuetsu EQ. to back-calculate equivalent friction coefficients mobilized during the failure.

Methods:
A series of shaking table model tests are first carried out to investigate the energy balance in a model slope made from dry sand. The earthquake energy directed to slope failure is measured by an innovative test method using free decay vibration given by a spring-supported shake table (Fig.1) and successfully quantified (Fig.2). The test results are then compared with a simple rigid block model to develop an evaluation method for slope deformation based on the energy concept (Fig.3).

Major findings:
Theoretical and experimental study has revealed the followings;
1) In an innovative shake table model test with different slope inclinations and different input frequencies, each term in the energy equation (1) involved in the failure of the model slope was quantified,

\[-\delta E_p + E_{EQ} = E_{DP} + E_K\]  \hspace{1cm} (1)

where, \(\delta E_p\) : potential energy, \(E_{DP}\) : dissipated energy in failed slope, \(E_K\) : kinetic energy.

2) The model test yielded a unique relationship, independent of input frequency, between the energy \(E_{EQ}\) and residual slope displacement \(\delta_r\) for various slope inclinations \(\beta = \tan \theta\) (Fig.4). The \(E_{EQ}\) versus \(\delta_r\) relationship shows a clear threshold of \(E_{EQ}\) below that, \(\delta_r = 0\), which is again independent of frequency. This indicates that not only residual displacement but also initiation of slope failure can be determined uniquely by the energy \(E_{EQ}\).
3) Comparison of the test results with the model (Fig. 3) indicates that a formula;

\[ E_{EQ}/Mg = (\mu - \beta)\delta_r/(1 + \mu\beta) \] (2)

based on the rigid block model can almost perfectly emulate a sand slope displacement despite the big difference in failure modes, provided that an appropriate friction coefficient \( \mu = \tan \phi \) can be given (Fig.5).

4) A simple graphical method to evaluate residual slope displacement is proposed (Fig.6) in which the displacement is evaluated from slope profile, equivalent friction coefficient \( \mu \) and earthquake energy \( E_{EQ} \). For saturated slope, the equation (2) is replaced by

\[ E_{EQ}/Mg = (\mu_{sat} - \beta)\delta_r/(1 + \mu_{sat}\beta) \]

\( \nu = 0.857 \)

\[ \mu_{sat} = \mu_{sat}(\phi_{sat}) \]

\( \phi_{sat} \)

\[ \phi_{sat} = \tan^{-1}(\mu_{sat}) \]

\( \beta \)

\[ \beta = \tan^{-1} \frac{\delta_r}{\delta_i} \]

from that of the tip of failed soil mass (Fig.9).

5) Quite unexpectedly, the runout distance increases with decreasing initial slope gradient and also with increasing volume of the displaced soil irrespective of the failure types, A, B and C. (Fig. 10, 11).

6) The displacement of the centroid may represent a travel distance of failed slopes because it differs little

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from that of the tip of failed soil mass (Fig.9).

7) Quite unexpectedly, the runout distance increases with decreasing initial slope gradient and also with increasing volume of the displaced soil irrespective of the failure types, A, B and C. (Fig. 10, 11).

8) The energy approach applied to the DEM database of the failed slopes revealed that the friction coefficients \( \mu \) back-calculated from many failed slopes are almost proportional to the initial slope gradient \( \beta_0 \) (Fig.12). This is quite different from artificial slopes in which \( \mu \) is considered independent of \( \beta_0 \).

9) The back-calculated friction coefficients \( \mu \) are lower than the initial slope inclinations \( \delta \) in larger volume slope failures, indicating that the failed soil mass first

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\[ \phi_{sat} = \tan^{-1}(\mu_{sat}) \]

\( \beta \)

\[ \beta = \tan^{-1} \frac{\delta_r}{\delta_i} \]
accelerated and then decelerated due to gentler or reverse slopes in down-slope sections. (Fig. 12).

10) The back-calculated friction coefficient tends to decrease with increasing debris volume irrespective of the failure types, A, B and C. This trend is very consistent to that indicated by Hsu (1975) for huge landslides (Fig. 13).

11) For slope failures of large volumes, the energy ratio $-\delta E_p/E_{EQ}$ is tremendously large, indicating negligible contribution of the earthquake energy $E_{EQ}$ compared to the potential energy $-\delta E_p$ (Fig. 14). However, the earthquake energy still plays an important role as a trigger of the failure by decreasing friction coefficient rather than by directly driving the soil mass.

**Fig. 10** Initial slope gradient of failed soil mass $\beta_0$ plotted versus runout distance $d_m$ for 3 types of failures.

**Fig. 11** Volume of failed soil mass $V_f$ plotted versus runout distance $d_m$ for 3 types of failures.

**Fig. 12** Initial slope gradient of failed soil mass $\beta_0$ plotted versus runout distance $d_m$ for 3 types of failures.

**Fig. 13** Friction coefficient $\mu$ versus volume of failed slope $V_f$ compared with previous research on case histories of huge landslides.

**Fig. 14** Energy ratio $-\delta E_p/E_{EQ}$ versus volume of failed soil for 3 types of failures.

**Key papers:**
