Analysis of the Potential for Nearly Circular Slope Failure Using On-site Survey Information with Adverse Calculation

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Abstract:- Slope stability analysis is crucial for decreasing unwanted economical loss at mountain highways which are prone to damage from heavy rains. The objective of this study is to perform on-site investigation and adverse calculation of slope damage at a specified road section along Tai-27 highway in Taiwan. By analysing a total of 38 on-site survey results, it is found that the types of slope damage may include debris flow (26%), shallow soil layer sliding (26%), nearly circular sliding (8%), slope oriented sliding (3%), falling rock (11%), river erosion (13%), and others (13%). Based on available geological information at three locations with nearly circular slope failure, the adverse calculations using computer software show that these slopes all failed at a shallow soil layer. Some of the important soil strength parameters such as cohesion force and friction angle are estimated, and a critical sliding surface is predicted for a minimum safety factor. The results provide useful information for choosing a suitable engineering protection work at these hazardous locations by the relevant agency.

Key-Words: - mountain highway, circular slope failure, adverse calculation, on-site survey, factor of safety, cohesion force, friction angle, critical sliding surface

1. Introduction

The island of Taiwan is located in a sub-tropical region with an area of about 36000 km^2, where mountains occupy about two third of the total area. There are many national parks and resort areas in these elevated mountain areas. For convenience, some paved roads were constructed along the foothill side, and this road network is usually an important traveling corridor for the people living in the neighborhood and for those on vacation. However, previously published reports show that the mountain roads can be damaged by heavy rains, which may cause serious slope failure and result in considerable economical loss. Therefore, it is useful to investigate the characteristics of road conditions at these mountain areas by on-site investigation and by calculation using computer software. A suitable improvement work for slope stability, based on local environmental situation, can then be undertaken for the specified road section to prevent unwanted damages.

Slope failure may occur due to several reasons such as manmade development, geographical condition, earthquake, and rain. In accordance with moving forms of landslide, slope failure may be classified into falls, topples, slides, lateral spreads, flows, and their combinations [1-2]. In general, except for manmade reason, rain is the main factor for causing slope failure. At a specified road surface, rainwater will penetrate into soil layer and form a higher level of groundwater, thus reducing the stability of the slope, hence there is no lack of studies in this related field [3-6]. Approximate road damage models may include plane failure, wedge failure, circular failure, and toppling failure [7]. In mountain roads, when the slope has a circular failure, it usually includes a deeper sliding surface, which can result in a large loss of road foundation and hence increase the difficulty in repairing the road. Thus, it is better to pay more attention to mountain roads within heavy rain fall areas either from academic or practical standpoint.

The highway Tai-27, Located at the southern part of Taiwan as shown in Figure 1, runs mainly along the central mountain range, which suffers from serious road damage due to heavy rain brought by typhoon in each year. To further understand the damage patterns on this mountain road slope, a specified road section (start point to end point, 01k+200～24k+030, about 24 km in total length) in this highway is chosen to find its characteristics using on-site investigation. Furthermore, the purpose of this study is to perform calculation based on available local data using computer software. Some of important parameters, such as cohesion intercept and friction angle, to calculate soil strength can then be obtained from adverse calculations [8-9]. This computing may provide useful information for improving slope stability and for designing an engineering protection project in this area. In the next section, a basic equation for the method to analyze slope stability is introduced. Then, a classification scheme for road damages is discussed and an adverse calculation for the case of nearly circular slope failure is included for the specified road section. Finally, a conclusion is made, and a preliminary protection work is addressed and suggested for this specified mountain area.

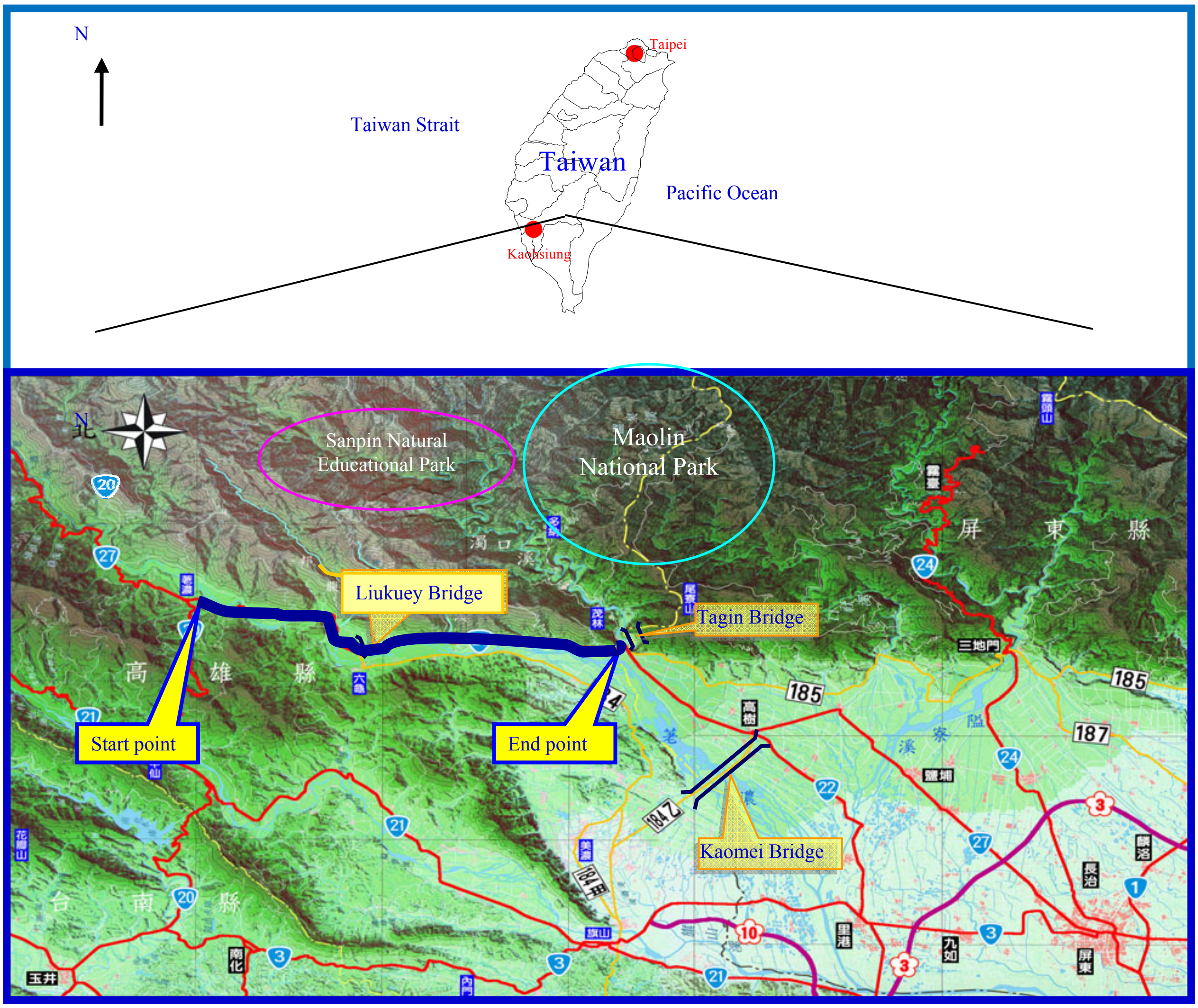

Figure 1. Sketch map of research area.

2. Equation and Software

Road slope condition is frequently influenced by natural and manmade factors, where the increasing of driving force and the decreasing of resisting force may be considered as the main reasons for causing damage. Using this concept with empirical formula, the stability of slope may be analyzed and suggestion may be made to improve its safety. This study focuses on the case of nearly circular slope failure which is based on limiting equilibrium method [10]. This approach assumes that the slope is not a deformable rigid body, while at the time failure occurs, it will be along a potential surface of the sliding block and result in total failure. The critical sliding surface is in general located at the place with the lowest factor of safety (*FS*), which is defined as:

$$FS = \frac{c + \sigma_d \tan\phi}{\tau_d} \tag{1}$$

where τ_d is the averaged shear stress at the potential damage surface; σ_d is the averaged normal stress; c is the cohesion force of slope material, and ϕ is the friction angle.

The solution procedure of limiting equilibrium method may be stated as the following steps: (1) assume a possible surface of sliding block with circular shape, and assume that the failure will occur at the same time along every point of the surface, that is the safety factor is equal for each point; (2) calculate shear stress on the sliding surface from static equilibrium resulting from all forces and moments; (3) compare material shear strength with shear stress to obtain safety factor; (4) assume another surface of sliding block, and repeat step (1) to step (3) for obtaining a new safety factor. By repeating step (1) to step (4) several times, the sliding surface with the lowest factor of safety is determined as one of the critical surface.

Further analysis of the above method may depend on the conditions of slope drainage [11]. In addition, the so-called slice method, which divides soil body of failure surface into several vertical slices, is probably the common approach for determining the factor of safety. From previous literature [12], it is known that the slice method depends on static equilibrium relationship, which can be formulated in different ways such as Felleniu ordinary method, Bishop simplified method, Janbu simplified method, Janbu rigorous method, Morgenstern-Price method, and Spencer method. Among these methods, Bishop simplified method assumes the force acting between slices is only along the horizontal direction, which is simple and has a computation error of only about 0-6% when compared with the rigorous method [13-14]. Thus, this method is frequently applied by practising engineers, and is used in the present study for calculating factor of safety.

From analysis of force equilibrium, the safety factor for the Bishop simplified method may be written as:

$$FS = \frac{\Sigma\left\{c \cdot 1 + \left(N - u \cdot 1\right)\tan\phi\right\}}{\Sigma W \cdot r \cdot \sin\alpha} \tag{2}$$

where W is the weight of each slice; N is the normal force at slice bottom; r is the radius of sliding circle; α is the inclined angle at midpoint of slice bottom; u is the hydro-pressure at midpoint of slice bottom; c and ϕ are as defined in equation (1). With this equation, the factor of safety can be calculated using the package Slope Stability Analysis Software (STABL). The original program of STABL was developed by Ronald A. Siegel at Purdue University in 1975, and can be used for finding general solution of slope stability problems by the limiting equilibrium method. This software has different versions including the newer GSTABL7 developed by Garry H. Gregory, but all are well accepted for generation of the potential failure surfaces, for the subsequent determination of the more critical sliding surfaces and their corresponding safety factors [15-17].

There are many factors that may affect the stability of slope such as geographical condition, topography constitution, and soil strength parameter. Previous studies showed that the accuracy of using adverse calculation will depend upon the input parameters, which may include pore water pressure, c value, ϕ value, survey accuracy of geography, and soil unit weight [18-19]. Therefore, the reliability of analyzing slope stability may be increased if these parameters can be obtained accurately. The procedures of adverse calculation using GSTABL7 for nearly circular slope failure have following steps: (1) measure possible critical sliding surface and original slope surface on-site; (2) obtain unit weight and c value from boring test data, and input these parameters with slope boundary conditions, the corresponding factor of safety is then found from the assumed ϕ value; (3) keep calculating until factor of safety reaches 1.0, and the corresponding ϕ value can be considered as on-site friction angle; (4) compare on-site c - ϕ curve with boring test data, and estimate possible slope failure surface if no protection action is taken before the next storm with heavy rain.

3. On-site Survey & Computing

An on-site survey is essential to understand the characteristics of the slope at the specified road section, which may include location, direction, gradient, width, height, stratum category, planting, failure style, water seepage, original protection, and other items. A total of 38 slopes within the present studied area were investigated and several on-site information were recorded, where type of slope failure is of primary concern in this paper. From survey information, six basic types of slope damage were identified, including debris flow, shallow soil layer sliding, nearly circular sliding, slope oriented sliding, falling rock, river erosion, and others. As seen in Figure 2 is the distribution of slope for each damage type, the amounts and percentages are 10 (26%), 10 (26%), 3 (8%), 1 (3%), 4 (11%), 5 (13%), and 5 (13%) for debris flow, shallow soil layer sliding, nearly circular sliding, slope oriented sliding, falling rock, river erosion, and others, respectively.

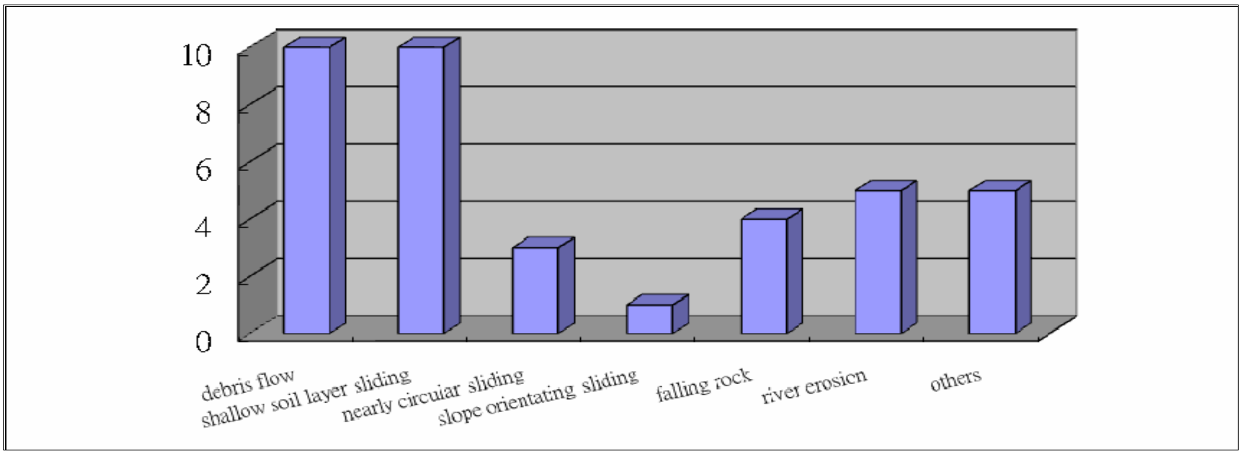

Figure 2. Distribution of slope damage types.

Heavy rains brought by typhoon may result in an increasing of pore water pressure within the stratum, and there is a relative increase in lateral soil pressure in this specified area, and this may cause different types of slope damage. Further, friction force is decreased between soil layers due to the huge amount of rainwater, and thus it can be found that the cases of debris flow and shallow soil layer sliding occupy more than one half (52%) of the total slope damage types. Although there are not too many slope failures of the nearly circular sliding type (8%), it usually has the potential for greater influence on the losses of road foundation. As this failure type will increase the difficulty of road recovery, it is better to check this case by using adverse calculation to minimize unwanted damage in the next event of heavy rain.

For a mountain highway, the case of nearly circular slope failure often occurs on the place where its soil body has a uniform thickness, and its sliding depth is about 3*m* below ground surface. In the area studied here, there exist three places with nearly circular failure, and the exact locations are at (a) 01k+200, (b) 13k+730, and (c) 18k+650, respectively. Table 1 shows the on-site observations for these failures, and it can be seen that the inclined angles are all over $40°$, and the plants seem unable to grow well under such sloping conditions and hence cannot be used to reduce failure. As rainwater is one of the major factors to affect nearly circular failure, the wet condition for the second location may reflect a higher groundwater level, so monitoring of water level may be required in this region to understand the actual effect of raining. Additionally, only the first case has an original engineering protection work, but because the existing concrete retaining wall was not constructed to a sufficient soil depth, it could not resist the sliding force of soil body and slope failure became an inevitable consequence in this location.

Table 1. On-site information for the case of nearly circular slope failure.

Location	Inclined angle (^{o})	Height (m)	Width (m)	Seepage condition	Planting	Original protection
01k+200	65	28	20	dry	sparse	concrete retaining wall
13k+730	41	20	40	wet	sparse	none
18k+650	51	20	10	dry	sparse	none

Basically, reference to a detailed road geological survey data is required in repairing slope failures. Due to the changing and complicated geological condition, an updating of survey data is useful in designing a suitable engineering work for the specified slope. The parameters of soil strength have a significant influence on the performance of slope repairing work. An on-site boring test and a laboratory tri-axial test are in general taken to obtain c and ϕ values. However, it may be doubtful that the chosen sample of the boring test represents the actual correct soil property for the entire slope condition. Besides, the tri-axial test is relatively costly and time consuming. Therefore, these tests are not often carried out in practice for preventing road calamity. On the other hand, the parameters c and ϕ can be determined if slope sliding surface and groundwater level can be obtained theoretically. In the next, an adverse calculation is performed using software GSTABL7, which can provide some of useful information for the three nearly circular slope failures.

For the type of nearly circular slope failure, Picture 1 shows the actual profile (A-A) of slope failure at location 01k+200. Because no direct experimental data is available in this region, it is hard to evaluate its sliding surface from computing result. But from the survey result of the mountain area for the whole island of Taiwan by Bureau of Soil Conservation, Council of Agriculture from the year 1986 to 1998, it can be seen that the ϕ value of cohesive soil range is between 17.7° to 37.7°. By using this estimation, and obtaining the soil unit weight r = 2.02 from on-site sample, the relationship between cohesion force and friction angle (c - ϕ) with factor of safety FS = 1.0 shown in Figure 3 can be calculated. The plot exhibits that the slope failure occurs in a shallow soil depth, and if ϕ value range is between 28.0° to 34.0°, then c value range is possibly between $0t/m^2$ to $1.5t/m^2$.

Picture 1. Actual profile of slope failure at 01k+200.

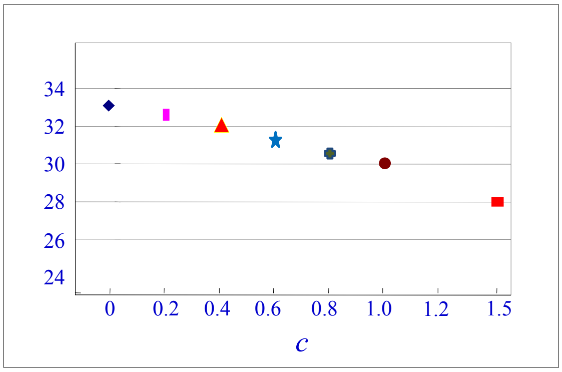

Figure 3. Relationship of c - ϕ values at 01k+200.

Now for the cases at locations 13k+730 and 18k+650, as there are on-site geological boring data for the road section in the present study [19-20], it is possible to perform adverse calculations by using available computer program. For the first case, Picture 2 shows its actual profile of slope failure (B-B). The tendency of slope failure can be estimated by inputting unit weight r = 1.6 and cohesion force c = 0, to obtain friction angle ϕ=31.5° for the entire slope when factor of safety equals 1.0. A reasonable agreement of actual profile and solution from GSTABLE7 calculation is shown in Figure 4. Additionally, the friction angle matches with boring test result ϕ=30°-35°, which can prove the reliability of using adverse calculation for this case. The computing result is displayed in Figure 5, it is seen that the indicated line surface with lowest safety factor (FS_{min} = 0.782) has the highest possibility of sliding the next time if no protection work is constructed on this slope.

Similarly, the actual slope failure profile (C-C) for the second case is displayed in Picture 3, and a comparison of actual profile with GTABLE7 solution is shown in Figure 6. It can be seen that the trend of the calculated surface of slope failure is in reasonable agreement with the actual result in the picture. For the computing results with parameters r = 2.07 and c = 0 to obtain ϕ=36°, the critical surface for minimum safety factor FS_{min} = 0.639 can then be predicted and shown in Figure 7. In general situation, the critical sliding surface will occur in a shallow layer if the property of soil has a high friction angle with a low cohesion force. On the other hand, if the property of soil has a low friction angle with a high cohesion force, then the critical surface will occur in a deep layer. Therefore, two cases of slope failure mentioned above are currently in unstable conditions. They will have the second nearly circular failure in a shallow layer, if no further action is taken to repair the slopes before the next heavy rain.

Considering the wide range of functions for the slope, the two types of slope protection work may be classified as: (1) anti-wind or anti-washing slope surface protection work, (2) anti-slip or anti-landform retaining wall protection work [20]. For the first type, the major concern is the choice of planting technique for covering the bare slope surface to decrease wind or rainwater damage. Because this type of protection work is unable to resist lateral soil pressure, it is only suitable for mild slope or rock slope area. For the second type, there are several protection works such as gravity retaining wall, semi-gravity retaining wall, reinforced retaining wall, and anchor pull retaining wall can be chosen to increase slope stability. Since each slope protection work has its own advantages and disadvantages, it is better to consider on-site conditions such as geographical, hydrological, topographical, and external loading for making a suitable choice to fit the actual requirements.

Picture 2. Actual profile of slope failure at 13k+730.

Picture 3. Actual profile of slope failure at 18k+650.

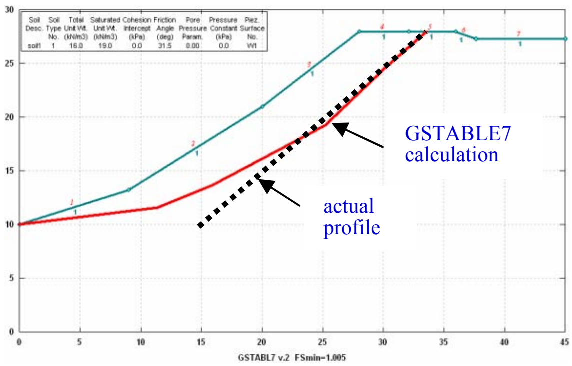

Figure 4. Comparison of result at 13k+730.

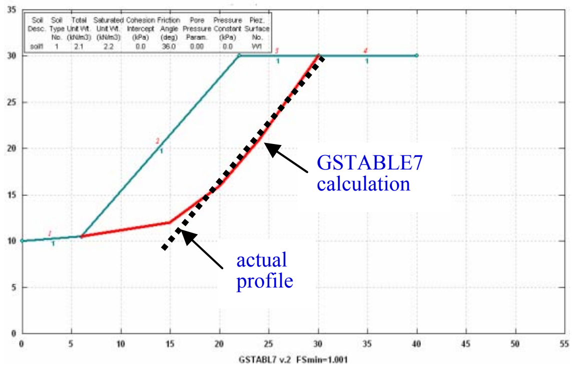

Figure 6. Comparison of result at 18k+650.

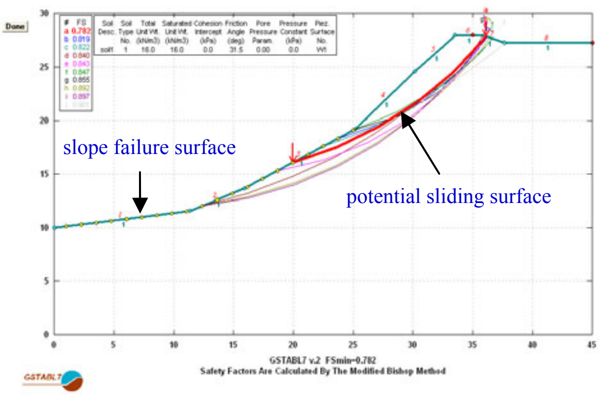

Figure 5. Slope failure surface at 13k+730.

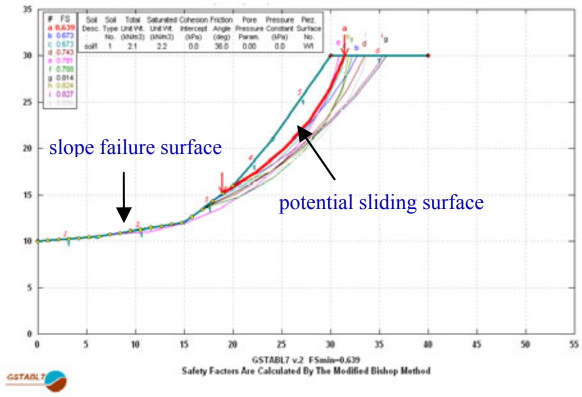

Figure 7. Potential sliding surface at 18k+650.

4. Conclusion and Suggestion

Mountain road condition is frequently affected by heavy storm due to typhoon experienced each year in Taiwan. The typhoon may bring a lot of rain water, which infiltrates the cracks in the highway slope and result in a large scale disaster due to land slide. This study performed an on-site investigation and computation for slope failure along a specified road section, including 38 locations between Laonung and Tajin in the Tai-27 mountain highway.

The results of the study show that the cases of debris flow and shallow soil layer sliding occupy 52% (20 locations) of the total slope damage types. The nearly circular slope failure occupied only 8% (3 locations) of the total cases of damage, but this type usually has a greater influence on the losses of road foundation and which may cause a potential second land slide. Therefore, the adverse calculations by using software GSTABL7 were executed for these locations to estimate some of the important soil strength parameters. The soil strength parameters including cohesion force and friction angle were estimated from their relationship, and a potential second land slide surface was predicted with minimum factor of safety for these nearly circular slope failures.

Overall, slope failure due to heavy rain at a specified section of mountain highway might cause tremendous economical loss, hence the public needs to be cautioned and the choice of engineering protection work has to match the on-site conditions to ensure its effectiveness. In the following are suggestions based on the results:

(1) At 6k+500～7k+500, 10k+200～20k+800, and 24k+300～24k+940, river erosion is the main reason to cause slope failure in these locations. It requires an installation of shore protection work and uses a combined foundation to strengthen its stability. It also needs to make precaution at upper road slopes, as these areas exhibit a tendency of small scale land sliding at shallow soil layer.
(2) At 6k+500～7k+000, and 15k+900～21k+100, many old alluvia are accumulated at the slopes, and those may be easily affected by heavy rains. Thus, it is better to clean the old alluvium at shallow layer in advance, and installs a temporary drainage system to prevent large scale land sliding during the storm period.
(3) At the location of 19k+400～24k+940, it requires to construct some of engineering protection works such as intercept net, planting net, concrete spray, and ground anchor, to prevent falling rocks. A warning sign or alarm may be set up in this falling rock area for increasing road safety.
(4) Finally, for more serious slope damage areas, three methods including occurring prevention, flowing control, and accumulating place, can be used to reduce damage from debris flow. For the case of nearly circular slope failure, various types of retaining wall and planting technique depend on actual geological conditions may be applied to increase its slope stability.

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