A PROPOSAL FOR REVERSE CALCULATION METHOD TO OBTAIN COHESION AND INTERNAL FRICTION SEPARATELY ON A SLIP SURFACE

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Abstract

In case of stability analysis for actually failed slopes, reverse calculation method is usually adopted to obtain correlation between two shear strength constants, assuming that safety factor is unity. However, each value of two constants is not settled of itself from the correlation, but must be fixed either by disregarding the other or estimating the other with groundless value. But this mase can be clearly solved by adopting such conception that factor of safety of a slope based on a specified slip surface obtained by site investigation should be minimum compared with any one based on other slip surfaces slightly shifted from the original one. When applying this procedure, definite answer is always obtained in case of total stress analysis, and if an idea of pore pressure ratio is introduced, instead of static water pressure distribution, this procedure is also satisfactorily applied to the case of effective stress analysis.

1 INTRODUCTION

In case of stability analysis for actually failed slopes, shear strength of soil obtained from laboratory tests is not often effective to decide their critical state. For this reason, such a reverse calculation method is usually and widely adopted that a correlation formula between two shear strength constants on a slip surface is obtained assuming that safety factor is unity. However, each value of two constants is not settled of itself from the correlation, but must be fixed either by disregarding the other or estimating the other with a groundless value.

We can find some examples in the Proceedings of the Eighth International Conference on Soil Mechanics and Foundation Engineering held in Moscow in 1973. Maslov of USSR, suggests that the sliding angle for clay be assessed at 10° and that the cohesion value is evaluated from recalculation for landslide sites with safety factor F equal to unity. According to Watari of Japan, on the other hand, the cohesion of clay is supposed almost proportionate to the depth of slip surfaces at the rate of 0.10kg/cm^2 for each 10m depth and the internal friction angle is calculated by reverse operation in which the factor of safety is assumed to be 1.00 without artificial causes. But no explanation is added in respect to the ground of these values: perhaps this disposal is considered to be an expedient in order to make analysis possible.

Standing on the opposite thinking, however, it is admitted as a fixed method of stability analysis, that the most dangerous location of a sliding circle would be settled and the factor of safety of the slope would be obtained, if the shearing strength of soil is given along the slip surface. The reverse application of this method, therefore, will result in producing shearing strength of soil along the slip surface by slightly shifting the slip surface.

In this case the other condition for this method is the restriction that the safety factor on the detected slip surface is the minimum compared with those on any slip surface slightly shifted from the detected one. Such method as will satisfy this condition comes to be promising as a reasonable one to decide each component of shearing strength.

2 CONSIDERATON ON METHOD OF DETERMINING C AND ϕ

Simplified slice method on a circular slip surface is provisionally used as a means of stability analysis of slopes. Assuming the location of a slip surface, the relationship between c and tan ϕ is expressed as a straight line AB in Fig. 1. In case of safety factor equal to unity, the relationship is indicated with a line AB on a diagram with c-tan ϕ cordinates. If we choose a point within the region I of the inner side for the origin from this line, a set of c-tan ϕ values expressed with this point will give a safety factor less than unity; on the contrary, another set of c-tan ϕ values chosen within the region II of the outer side for the origin from AB line will give a safety factor more than unity.

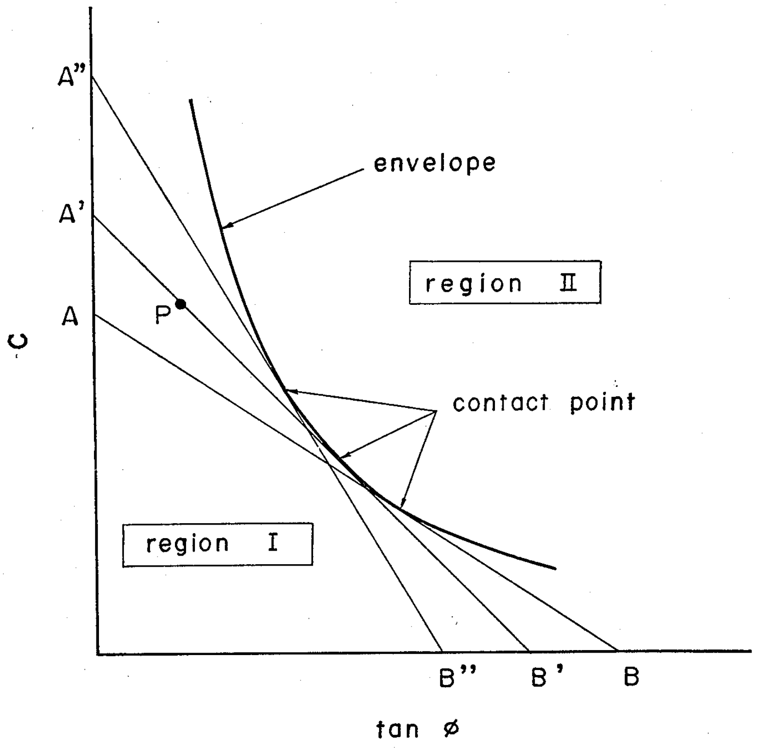

Fig. 1 Illustration about how to decide c and ϕ

When a slip surface is slightly shifted from the original location, AB line will move accordingly to a new position, such as $A'B'$ or $A''B''$. If we choose a point P on $A'B'$ line as shown in Fig. 1, it yields safety factor more than unity in regard to AB, but less than unity in regard to $A''B''$. The limit of the range, therefore, that yields safety factor more than unity for every slip surface, is indicated with an envelope formed by a group of those straight lines. In this case, a point chosen within the range outside of the envelope for the origin will give safety factor more than unity; on the contrary, a point chosen within the envelope will give safety factor either more or less than unity according to the position of each straight line.

Each straight line forming an envelope will make contact with the envelope at a single point and a unique point that is not held in common with other lines. If those values of c and ϕ represented by the contact point are used, safety factor will be exactly equal to unity, for the slip surface connected with the straight line passing the contact point, but safety factor for other slip surfaces will be more than unity, so far as the envelope is convex against the origin. Such a conclusion, therefore, will be deduced that it is limited to the case of adopting c and $\tan\phi$ values given by the cordinates of contact point held in common by the envelope and the straight line connected with the actual slip surface, in order to reason out that a landslide will inevitably occur on the confirmed actual slip surface.

Group of the straight lines should be constructed with a definite way; otherwise, the result will be to compare each one with incomparable. In case of sliding of a slope essential elements forming geometrical figure are slope length and depth of sliding mass, assuming that inclination of a slope is fixed; therefore, let us try to examine stability of a slope by fixing our eyes upon these two elements.

In case of changing slope length under fixed depth, group of straight lines forms no envelope within the positive region of both c and ϕ. The reason is that slope length is a decisive element for stability of slopes, and that safety factor of a slope will decrease against slope length, for any combination of c and ϕ under fixed depth.

So we will try next to change depth of sliding mass under fixed slope length. In this case group of straight lines always forms an envelope within the positive region of both c and ϕ, on the occasion of total stress analysis or no pore water pressure, and it is possible to decide c and ϕ corresponding to the location of circular slip surface.

If effective stress analysis is requested under presence of pore water pressure, insufficient result will be obtained in most cases, because an envelope is formed outside of the positive region of either c or ϕ, assuming static water pressure distribution. This troublesome situation will be solved, however, with a realistic assumption that pore water pressure at slip surface is proportional to the overburden pressure; in this connection the average ratio of the former to latter is called by using as pore pressure ratio, $\bar{r}_u$, after Imperial College Group.

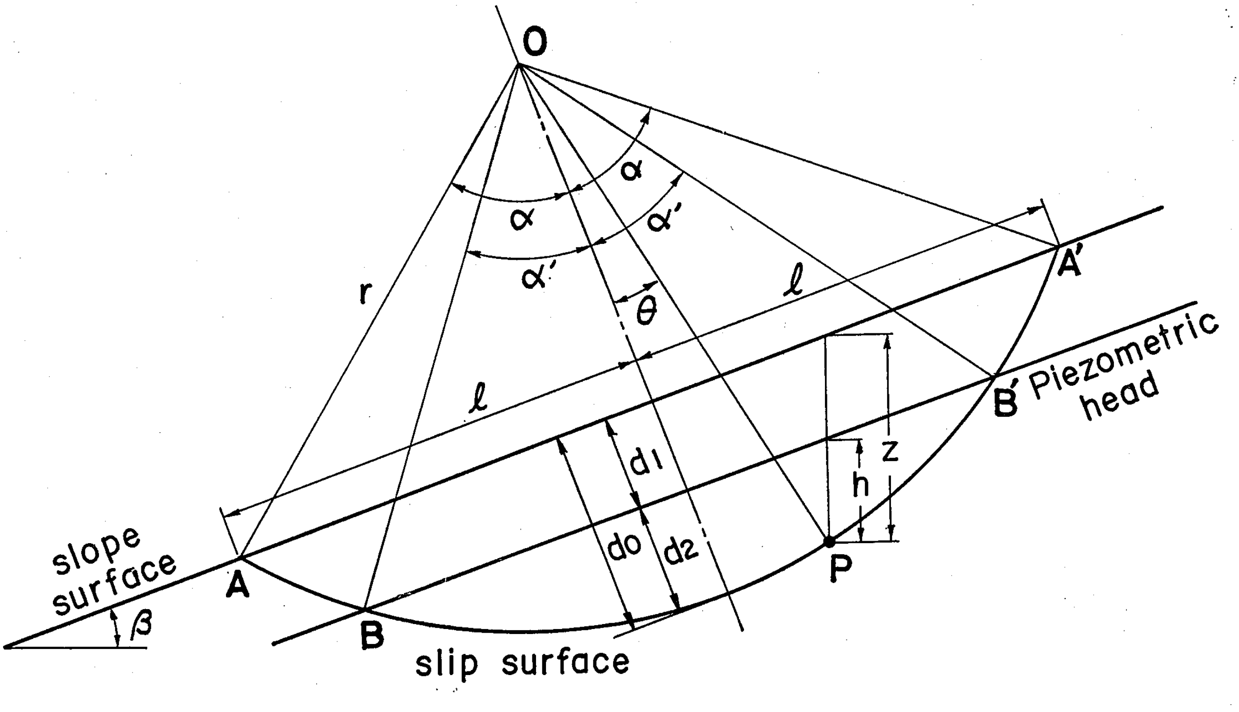

Fig. 2 Graphical indication of symbols

3 GENERAL TREND OF ENVELOPE

In order to make analysis possible, let us consider a simple slope as shown in Fig. 2. In this figure, line AA' means surface of a slope, line BB' be piezometric head, $ABB'A'$ be circular slip surface and o means the center of the circle.

The following formula is deduced from equilibrium condition between the weight of a slice, shearing resistance and pore pressure at the bottom at each point on the slip surface.

$$\sin\beta\frac{\sin^2\alpha}{2\alpha}=\frac{c}{\gamma l}+\frac{\tan\phi}{\cos\beta}\left[\cos 2\alpha\frac{\sin^2\alpha}{6\alpha}+\frac{\sin\alpha-\alpha\cos\alpha}{2\alpha\sin\alpha}-\frac{\gamma_W}{\gamma}\cdot\frac{\sin\alpha'-\alpha'\cos\alpha'}{\alpha\sin\alpha}\right]$$

where

β: inclination of slope,
α: half of center angle on slope length of sliding mass,
α': half of center angle on total length of piezometrice level cut by slip circle,
γ: unit weight of soil,
l: half of slope length and
γ_W: unit weight of water.

pore pressure ratio, $\bar{r}_u$, might be simply defined as

$$\bar{r}_u=\frac{d_2\gamma_W}{d_0\gamma}=\frac{1-\cos\alpha'}{1-\cos\alpha}\cdot\frac{\gamma_W}{\gamma}$$

where d_0 and d_2 are shown in Fig. 2. Then, α' is obtained with the following formula,

$$\cos\alpha'=1-\bar{r}_u\frac{\gamma}{\gamma_W}(1-\cos\alpha)$$

Based on these arrangements, an example of the relationship between c and $\tan\phi$ by means of total analysis is shown in Fig. 3, assuming β as 20°.

Another example of the relationship with positive pore pressure ratio is shown in Fig. 4. It shows that change of cohesion value corresponding to pore pressure ratio is not very large. Therefore, it is fully reasonable to adopt such a procedure that cohesion is obtained based on total stress analysis and then $\tan\phi$ corresponding to the cohesion is determined on the straight line of the actual slip surface.

It is more convenient to obtain a point of contact of an envelope to a tangent line from two points of intersection of the three neighboring straight lines, with the center line connected with actual slip surface.

Using this method we can obtain fixed values of c and $\tan\phi$ corresponding with the actual surface without confusion.

4 EXAMINATION ON ACTUAL EXAMPLES

a) *Takabayama Landslide*

In January, 1970, a landslide occurred on Iiyama Line of the Japanese National Railways and collapsed a half of Takabayama Tunnel, 187m in total length. This landslide is well-known in Japan by reason of the fact that forecasting of failure time of the landslide was announced officially by the railway authorities on the previous day and the result was that estimated failure time was only 6 minutes earlier than actual time : the progress of this incident was reported by us at the International Conference in Moscow, 1973.

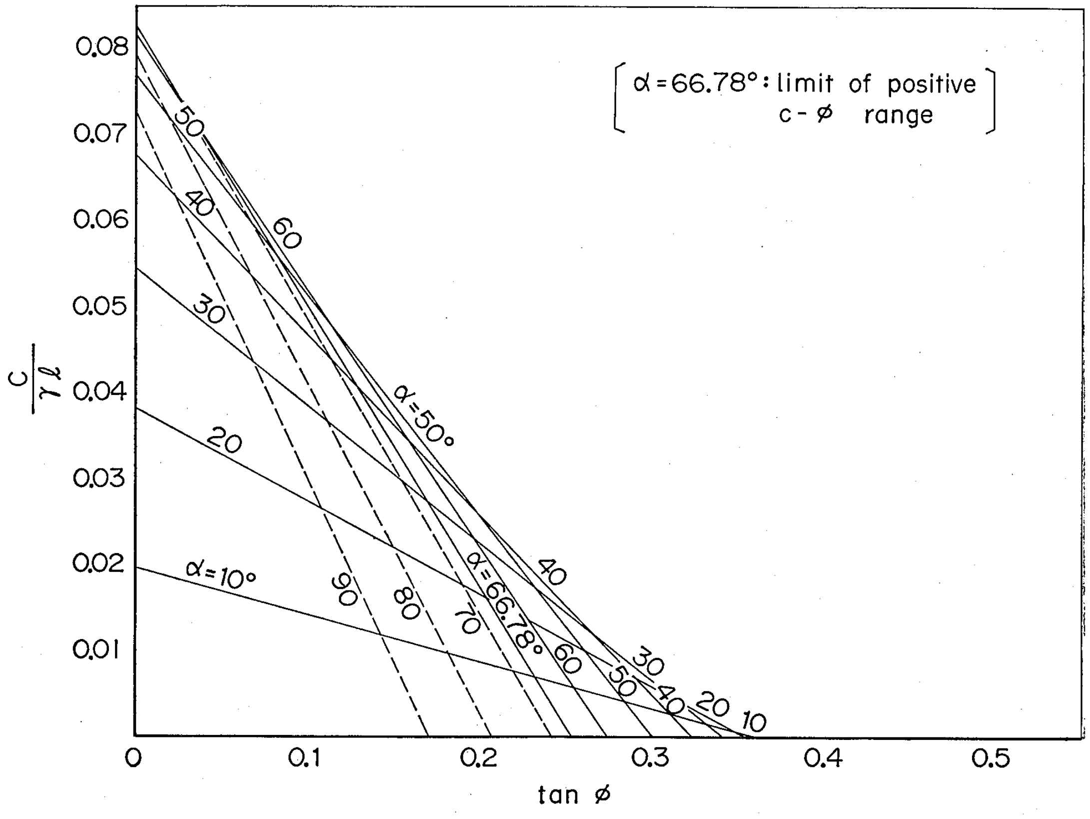

Fig. 3 An example of group of straight lines by means of total stress analysis ($\beta=20°$)

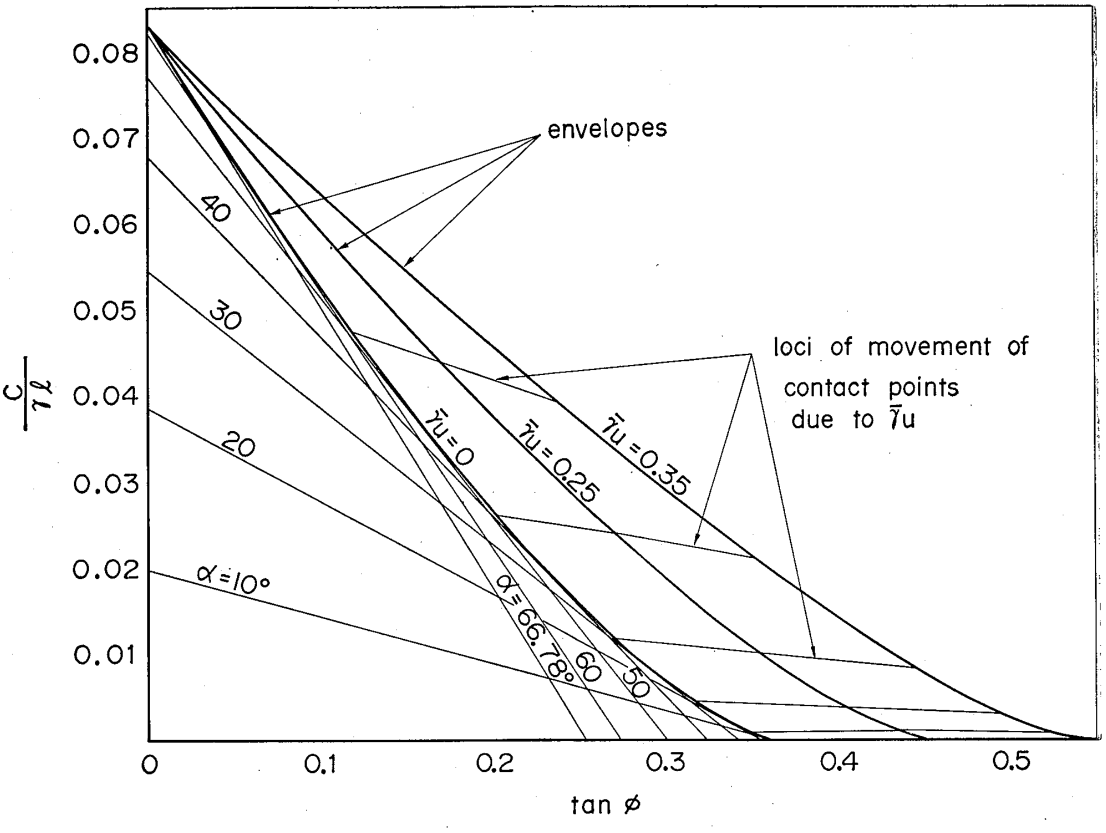

Fig. 4 An example of envelopes of group of straight lines corresponding to change of pore pressure ratio, by means of effective stress analysis ($\beta=20°$)

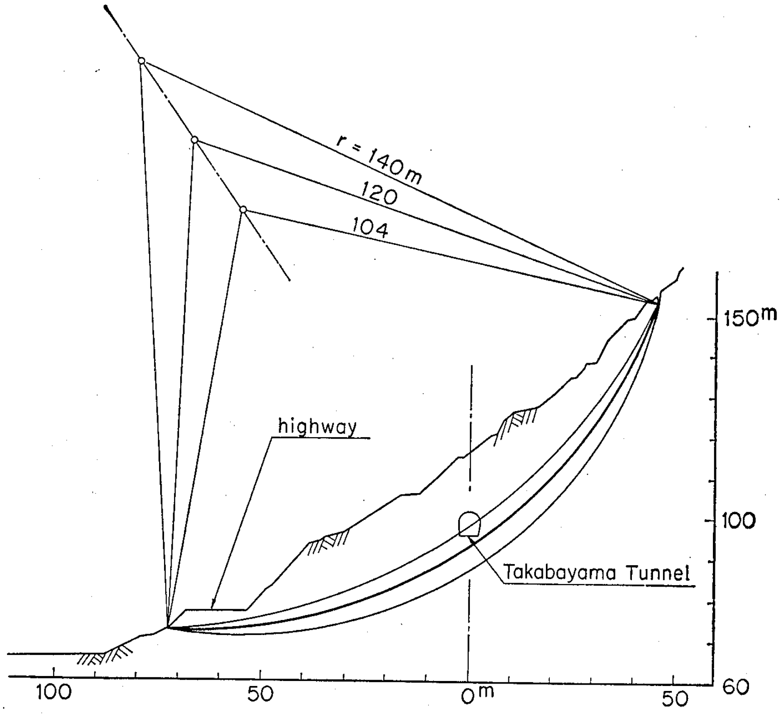

Fig. 5 A cross section of Takabayama Tunnel Landslide

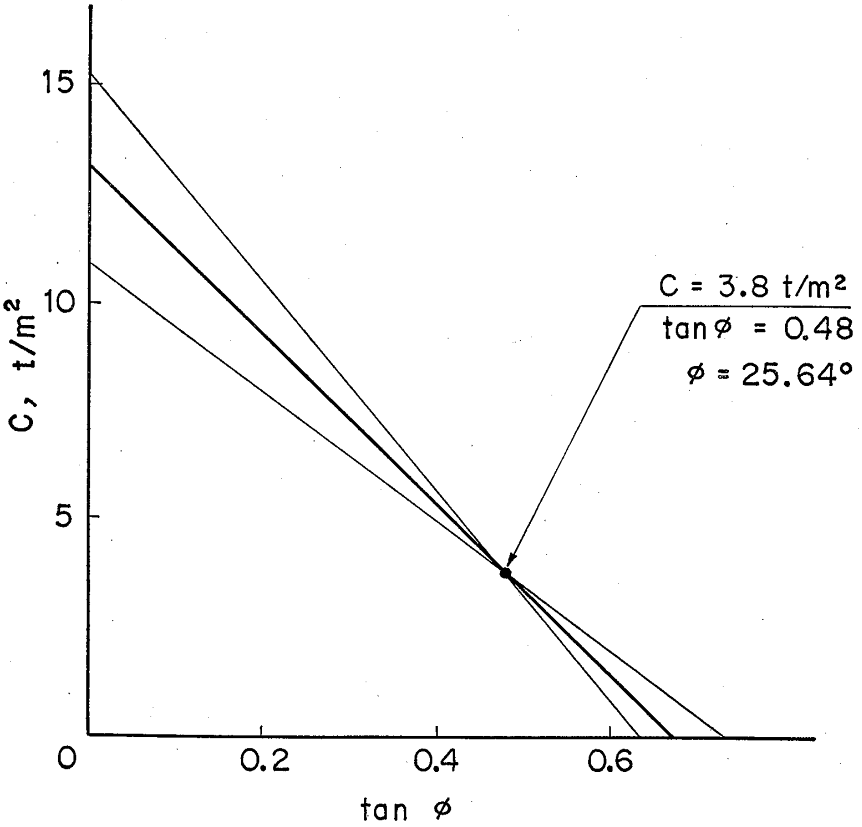

Fig. 6 c—tan ϕ lines of Takabayama Tunnel Landslide by means of total stress analysis

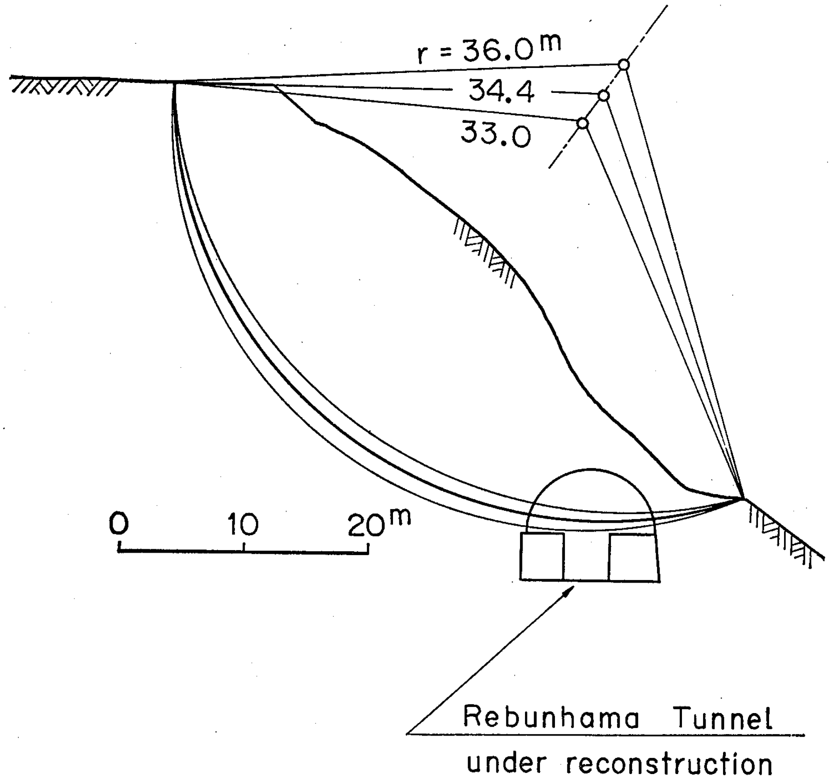

Fig. 7 A cross section of Rebunhama Landslide

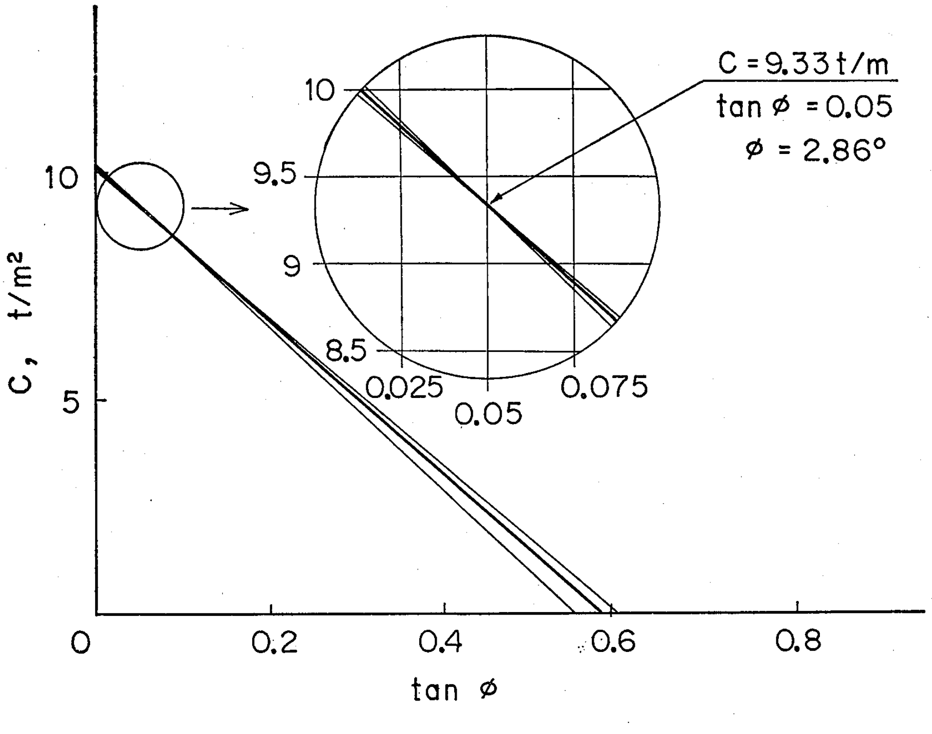

Fig. 8 c—tan ϕ lines of Rebunhama Tunnel Landslide by means of total stress analysis

Fig. 5 show a cross section of Takabayama landslide, where depth of slip surface were detected using pipe strain gauges embedded in boreholes. Actual slip surface and two temporary slip surfaces, slightly shifted at each side and passing both ends of actual one are drawn, c-tan ϕ lines connected to three sliding surfaces are shown in Fig. 6, by means of total stress analysis. From this figure the contact point on the envelope is determined and the following values are obtained.

$$c=3.8\ \mathrm{t/m^2},$$
$$\tan\phi=0.48, \qquad \phi=25.64°.$$

In consequence it is understood that both c and tan ϕ cannot be neglected.

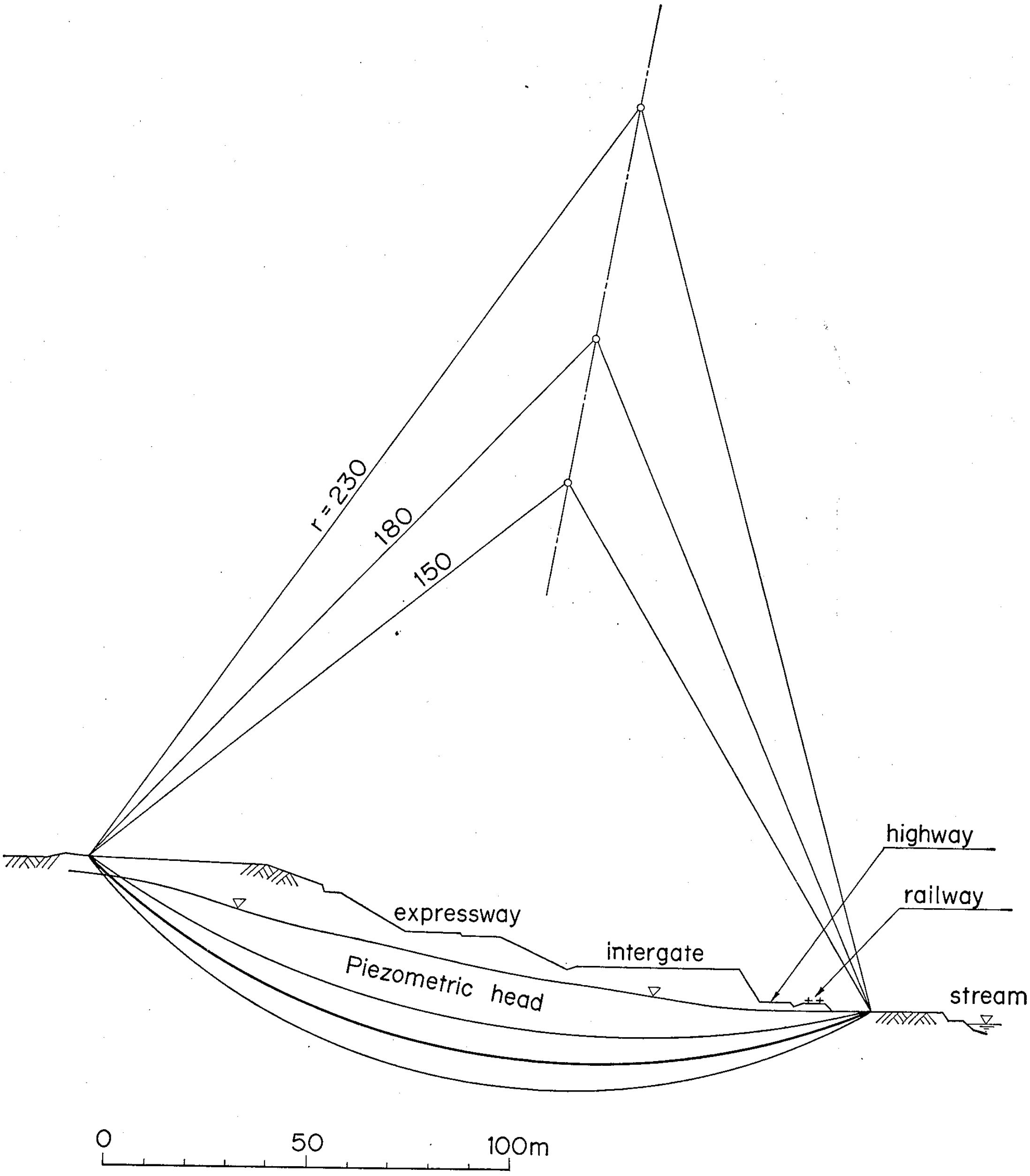

Fig. 9 A cross section of Nishimeihan Landslide

b) *Rebunhama Tunnel Landslide*

In 1973 a landslide occurred involving western part of Rebunhama Tunnel on Muroran Main Line, JNR, which was just under reconstruction for the purpose of doubling of tracks. Fig. 7 shows a cross section of the slide, and the result of treatment by means of total stress analysis is shown in Fig. 8. From this Figure following values are obtained:

$$c=9.33\ \mathrm{t/m^2},$$
$$\tan\phi=0.05, \qquad \phi=2.86°.$$

In this case, effect of frictional resistance may be neglected.

c) *Nishimeihan Landslide*

At a landslide around Kashiwara Interchange on Nishimeihan Expressway, which occurred in 1969, pore water pressure was being measured, and so reverse calculation of soil strength was tried by both means of total and effective stress analysis. Fig. 9 shows a cross section of the slide. According to such treatment as shown in Fig. 10 by means of total stress analysis, following values are obtained,

$$c=1.15\ \mathrm{t/m^2},$$
$$\tan\phi=0.159, \qquad \phi=9.03°.$$

As for treatment by means of effective stress analysis, pore pressure ratio $\bar{r}_u$ was adopted as 0.35 based on measured pore pressure, and following values are obtained,

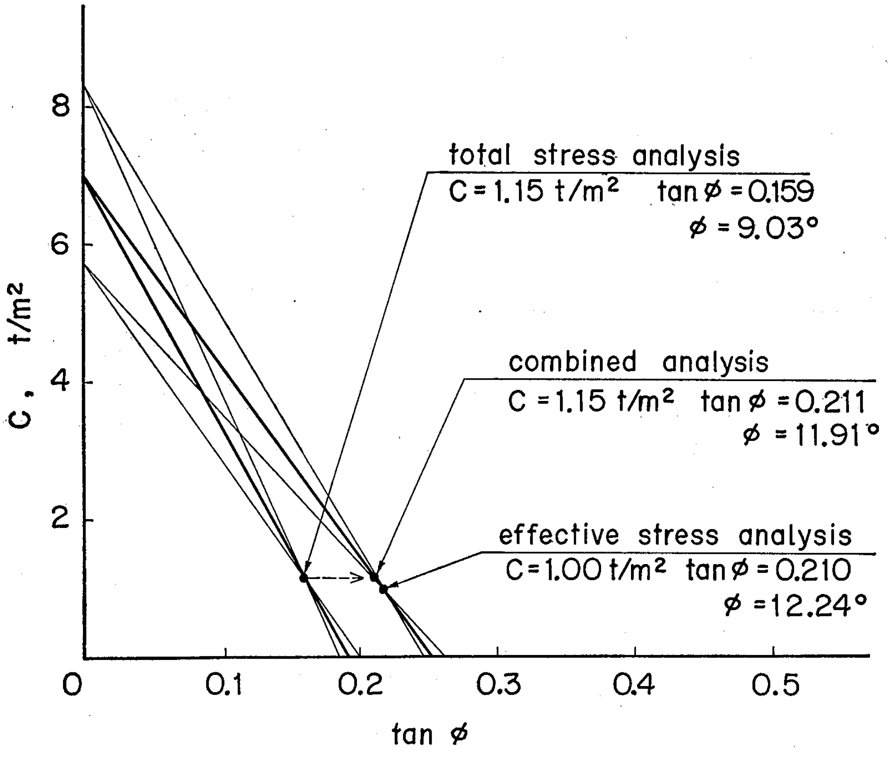

Fig. 10 c—$\tan\phi$ lines of Nishimeihan Landslide by means of three types of effective stress analysis

$$c=1.00\ \mathrm{t/m^2},$$
$$\tan\phi=0.210, \qquad \phi=12.24°.$$

As the value of cohesion obtained by means of effective stress analysis is not very different from that by means of total stress analysis, it is considered as an alternative method to determine the value of ϕ, using this cohesion in effective stress analysis. The result of this operative method is shown in Fig. 10 and provides following values:

$$\tan\phi=0.211, \qquad \phi=11.91°.$$

The result shows that this method is fairly available as an expedient one for effective stress analysis.

5 CONCLUSION

This reverse calculation method of c and ϕ is reasonable in logical contemplation by reason of the fact that a pair of adopted values of c and ϕ satisfies the condition of stability of slope on slip surface, and furthermore satisfies the condition of minimum safety factor, compared with those as any slip surface slightly shifted from the detected one. This method is satisfactorily applied not only to the case of total stress analysis, but also to the case of effective stress analysis, as an envelope is formed inside of the positive region of both c and ϕ, if an idea of pore pressure ratio is introduced.

This reverse calculation method, therefore, is considered very powerful and useful to obtain reliable values of c and ϕ, and worth while to employ as a means of collation.

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すべり面上に働く粘着力と内部摩擦角とを分離して求める逆算方法についての一提案

斎藤迪孝

概要

実際にすべりを生じた斜面の安定解析を行なう場合に，実験室で得られた土の剪断強度は，斜面の限界状態を決定するのに有効でないことが多い。そのために逆算方法が広く行なわれているが，これで c，ϕ の関係は求められても，それぞれの値は決定されないので，便法としてどちらかの値を無視するか，あるいはどちらかに適当な値を与えて他方を求めているが，その根拠はたしかではない。しかし，他方土の剪断強度として c，ϕ が与えられると，斜面の安全率が求められ，最も危険なすべり円の位置もきめられるのであるから，これを逆に適用すれば c，ϕ が求められる筈である。それは安定の限界条件を満足するだけでなく，その近接のすべり円の場合と比較して，安全率が最小であると言う条件をつけ加えることで条件がそろうことになる。

今，円形すべり面で最も単純な分割法を例として考えると，限界条件として特定のすべり面上で安全率が1であるとすると，その条件を満足する c と $\tan\phi$ は，それらを両軸とする座標上で直線関係をなす。すべり面の両端を固定しておいて，半径を変えることによりすべり面を上下に動かすと，それに応じて c-$\tan\phi$ 線は動き，それらの線群が図―1に示すように1本の包絡線を形成する。特定のすべり面と包絡線との切点をとれば，他のどの直線に対しても安全率は1より大きくなるので，その特定のすべり面において安全率は最小となる。それゆえ，その点の座標がそのすべり面に対する c，$\tan\phi$ を与えることになる。

理解を容易にするために，図―2に示すような記号を用いて，全応力により解析を行なうと，各すべり面に対応する線群は図―3に示すようになり，包絡線が形成されるのがわかる。間隙水圧がある場合は，静水圧分布を考えると，包絡線は c，ϕ のどちらかが負の範囲で形成されるので，現実的ではない。それで間隙水圧比 $\bar{r}_u$ の考えを導入すると，図―4に示すように，c，ϕ の双方が正の範囲で包絡線を形成するようになり，現実的に扱えるようになる。

事例として，高場山トンネルの地すべりの例を図―5および6に，また礼文浜トンネルの地すべりの場合を図―7および8に示す。どちらも全応力解析であるが，前者は c，ϕ 共に無視できないことがわかるが，後者では摩擦抵抗を捨てて c だけを用いても差支えないことが理解されよう。

また，西名阪道路の地すべりでは，間隙水圧を観測していたので，全応力，有効応力双方の解析が可能であって，その結果が図―9および10に示されている。この場合，有効応力法で解析を行なっても，全応力で求めた c を用いて有効応力の場合の ϕ を求めても，実質的には大差がないことがこの結果からわかるので，解析の便法として利用されよう。

以上のように，逆算方法で c，ϕ を分離して求めるには，その特定のすべり面での安全率が最小になることを条件として入れればよいわけで，これにより勝手なきめ方をしないですむことになり，合理的な方法と言えよう。