ESTIMATION OF DEFORMATION MODULUS BASED ON BACK ANALYSIS OF MONITORING DATA IN UNDERGROUND EXCAVATION

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ABSTRACT

Based on statistical study on large volume of field plate loading test data collected in Taiwan and mainland China, an empirical relationship of deformation modulus and RMR rating of rock mass was established. This relationship was further examined by the results of back analysis using monitoring data of underground excavation projects. The results show that deformation modulus of rock mass with fair or better quality would depend strongly on the strength of rock material. For poor or very poor rock mass, the modulus would depend less on intact rock property due to the presence of infill materials between rock fragments. This empirical relationship proposed was found to have the same trend as that suggested by Serafim and Perira but have significantly lower estimation, especially for weak rocks.

***Keywords**: deformation modulus, rock mass, rock mass rating, back analysis, plate loading test, underground excavation.*

GENERAL

Numerical modeling is an important approach in assessing the safety of underground construction, slope or large scale foundation in rock formation. In the modeling processes, estimation of mechanical properties of rock mass, including the strength and deformation characteristics and in-situ state of stresses, is of utmost importance for properly assessing the behavior of structure during construction or under service loading. Among the mechanical properties needed, the estimation of deformation modulus of rock mass has often been made by performing in-situ testing or using empirical relationships proposed by various investigators. In-situ testing has the merit of measuring the property directly at the site and hence gives most reliable estimation. This is often being done in important project covering limited project area, such as underground cavern, dam or nuclear power station. For project site covering large area or many geological formations, such as tunnel, it is usually unfeasible to carry out in-situ test to obtaining the deformation modulus in the design stage. Empirical relationships, instead, have been widely used for preliminary estimation.

The empirical relationships most widely used in engineering practice include those proposed by Bieniawski (1978), Serafim and Pereira (1983) and Barton et al (1980), which relate the deformation modulus to the rock mass rating index, such as RMR or Q. However, experiences with weak rocks in Taiwan showed that the empirical relationships developed mostly on strong rocks give significant over-estimation in modulus value. In some cases, it gives unreasonable estimation with modulus of rock mass greater than the intact core. Therefore, deformation modulus of rock mass depends not only on the rock mass quality but also on intact rock property. More recently, Hoek (1995) proposed a relationship between deformation modulus, geological strength index (GSI) and intact core strength. Chern et al (1997) also proposed empirical relationships for sedimentary rock and igneous/metamorphic rock respectively based on field plate loading test results collected from Taiwan and mainland China.

In this paper, deformation monitoring data from underground constructions were used to back-calculate the rock mass modulus, and the results were used to re-examine the empirical relationship proposed.

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PREVIOUS INVESTIGATIONS

As stated in the previous section, the widely used empirical suggestions often give unreasonable estimation of modulus value for weak rocks. A relationship of deformation modulus and rock mass rating RMR value was studied statistically for sedimentary and igneous/metamorphic rock respectively using the large scale plate loading test data collected from Taiwan and mainland China. Four separate empirical relationships for each type of rock as a function of intact core strength were obtained. In the proposed relationship, the modulus of rock mss degrades with decreasing RMR value from the upper bound modulus value of intact core. Thus, if the modulus value of intact rock is available, the modulus of rock mass can be establish. A correlation of intact rock modulus and core strength was also suggested, which enables the estimation of modulus of intact rock from the core strength conveniently. However, for practical reasons, four parallel lines for estimating the deformation modulus of rock mass for weak, medium strong, strong and very strong rocks were proposed. The results are shown in Fig. 1 and Fig. 2 for sedimentary rock and igneous/metamorphic rock, respectively.

From Fig. 1 and Fig. 2, it may be noted that for igneous/metamorphic rock, the data are mainly for strong and very strong rocks, and the data for lower strength rocks are rather limited and show larger variation. However, if the relationships for strong rock and very strong rock were considered, their relationships are quite similar in trend and magnitude. Therefor, instead of using two separate sets of empirical curves for sedimentary rock and igneous/metamorphic rock, only one set of curves was suggested for practical engineering application, and the results are shown in Fig. 3. This empirical relationship has been used by the authors in a number of underground excavation projects. Generally, good estimation in rock mass deformation around underground opening was achieved.

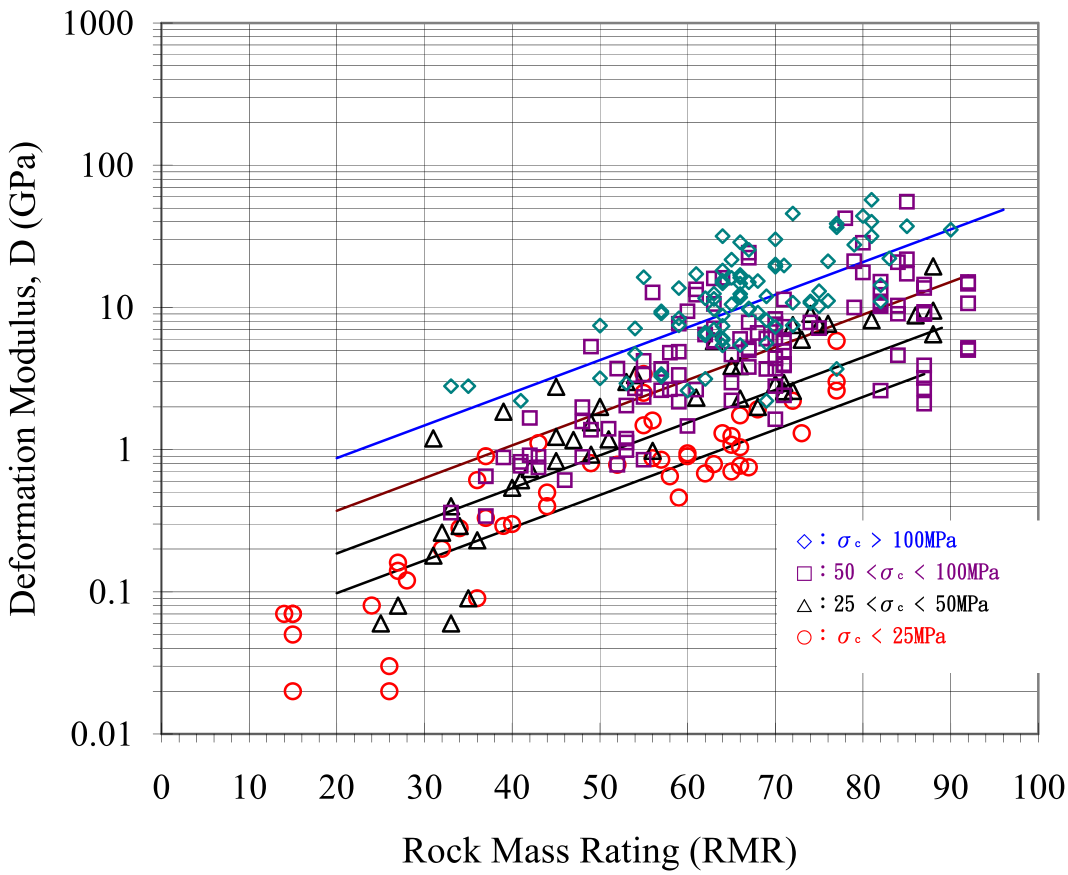

Fig. 1 Deformation modulus of rock mass vs RMR for sedimentary rocks of various rock strengths

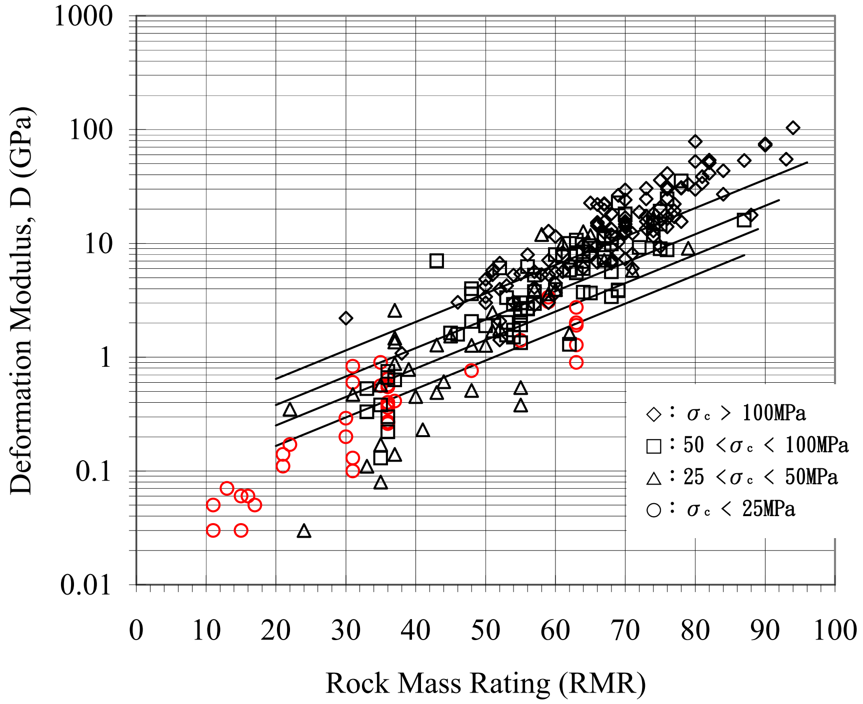

Fig. 2 Deformation modulus of rock mass vs RMR for igneous/metamorphic rocks of various rock strengths

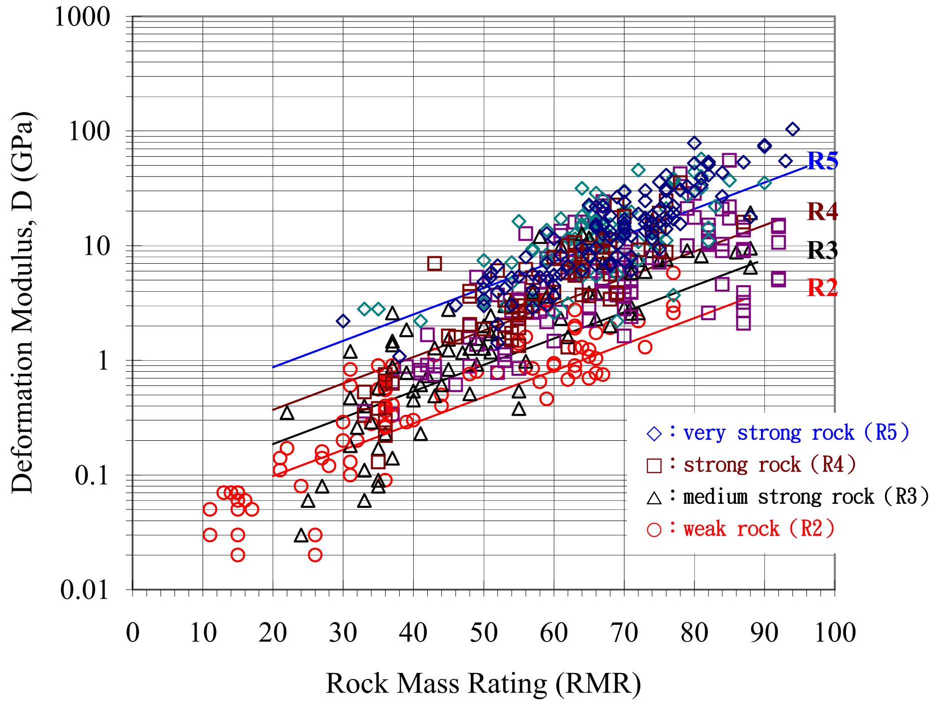

Fig. 3 Deformation modulus of rock mass vs RMR for sedimentary rocks and igneous/metamorphic rocks of various rock strengths

For very poor rock mass, the deformation modulus appears to degrade rapidly with decreasing RMR value. No clear trend of modulus value depending on the rock strength can be observed as indicated for better quality rock. It appears reasonable that the property of infill materials between rock blocks of highly fractured mass, instead of intact rock property, would dominate the deformation behavior. A tentative trend to include the very poor quality rock is shown in Fig. 4. The empirical relationship suggested will be re-examined by using the results of back analysis of monitoring data from underground excavation projects in Taiwan.

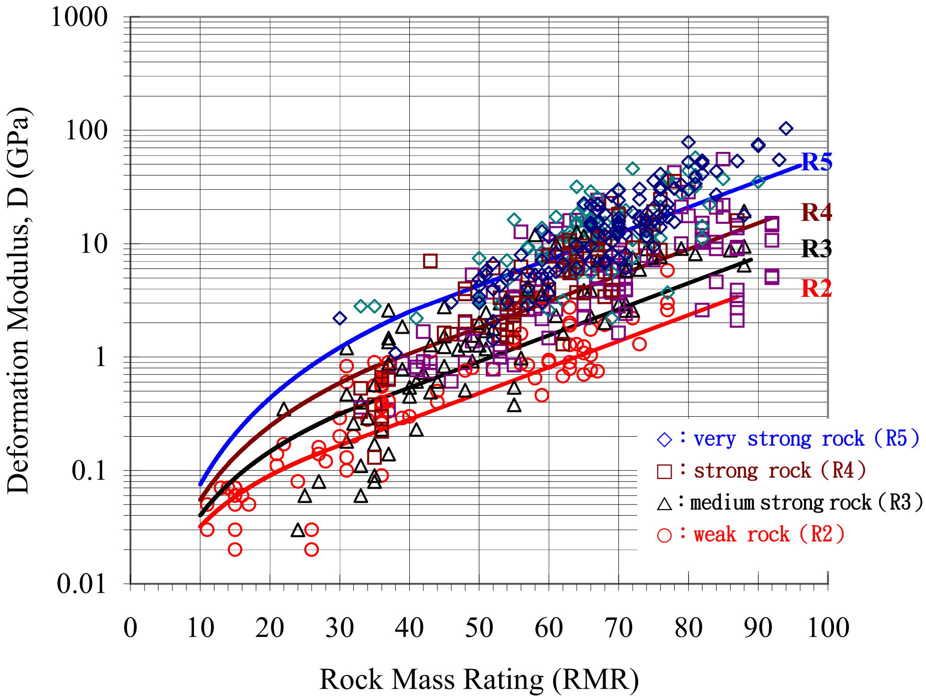

Fig. 4 Revision of proposed empirical relationship for rock mass with very poor quality

CASE HISTORIES OF UNDERGROUND EXCAVATION

The case histories of underground excavation project used for examining the empirical relationships described above are summarized in Table 1. The information include project name, rock type, geologic age, intact core strength, RMR value and back-calculated deformation modulus. Most of the cases are from Hsuehshan tunnel project. Several cases of large underground caverns of hydropower projects, including Mingtan, New Tienlun and Shilin, and Yuanshautsu flood diversion tunnel are also included.

Elasto-plastic analysis was adopted in back analysis using the computer code FLAC-2D. In the more recent analyses conducted in 2000 and 2004, FLAC-3D was used. In the analysis, the strength of rock mass was estimated by using Hoek-Brown criterion based on rock mass rating RMR value and intact core strength with further consideration of stress level encountered at the site. Modulus value was adjusted by trial and error in order to get the best match between the field monitoring data and the calculated deformation values. Special attention was made to consider the unmeasured rock deformation by the instruments, since pre-installed instruments are generally not available with the exception of Mingtan caverns in which complete deformations in the roof area were obtained by pre-installed extensometers from the pre-treatment galleries.

Since 2-D analysis can not simulate the development of rock deformation due to the advancing of excavation face, total final rock deformations have to be used for back calculation. To take the un-measured rock deformation occurred before installing instrument into account, the total deformation was estimated by using the relationship of deformation progress with advancing face distance as shown in Fig. 5. The relationship was established by using 3-D numerical analyses, and actual measured data with pre-installed instruments from Mingtan project are also shown in the figure. From the figure, considerable amount of deformation, about 20% to 30% of final value, would have occurred at the tunnel face, and more than 75% to 90% of final value at the location of one tunnel span distance from advancing face. Therefore, for the purpose of back analysis, it is preferable that the instrument is installed very close to the advancing face in order to reduce the error arising from deformation estimation.

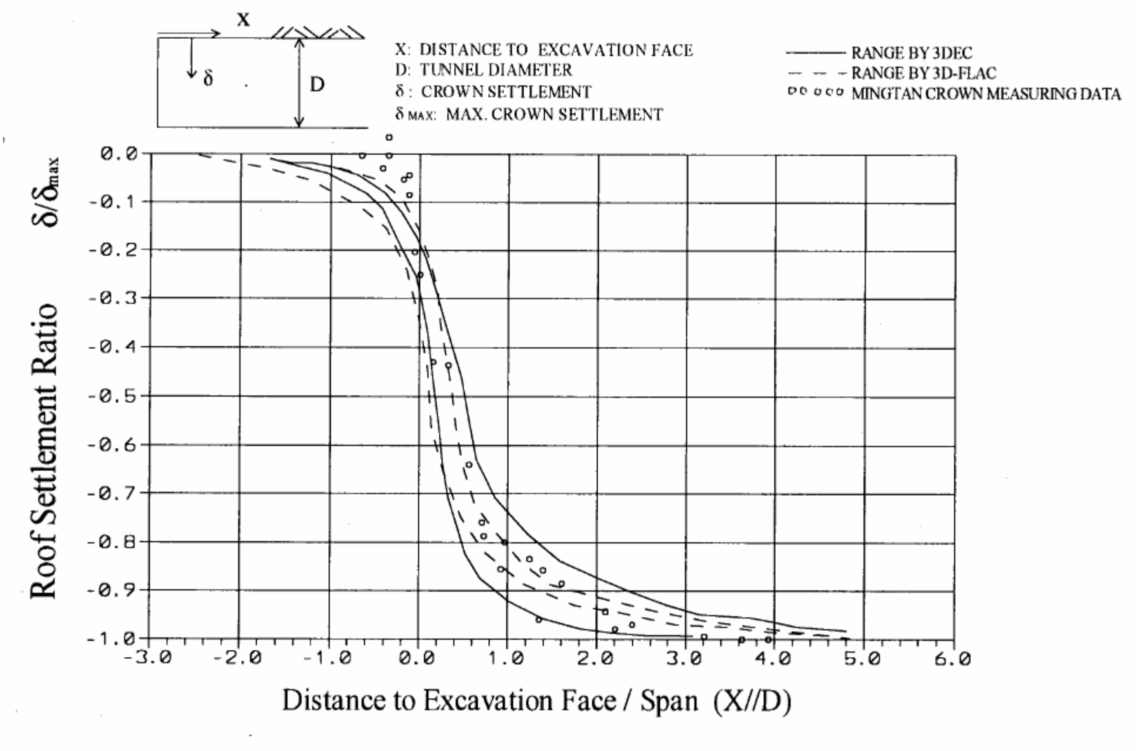

Fig. 5 Development of tunnel movement with the advance of excavation face

For 3-D analysis, it can simulate the advancing of excavation face. By matching the actual deformation measured would give the estimation of rock properties. However, it is still preferable that the instrument be installed as close to the advancing face as possible.

Hsuehshan tunnels pass through the Hsuehshan Ranges in northern Taiwan. In the tunnel horizon, it cuts through highly folded and faulted Tertiary formations of medium strong to very strong rocks. Numerous monitoring stations were installed during the construction of pilot tunnel and main tunnels by D&B method. Totally 17 sets of monitoring data were used for back analysis of deformation modulus of rock mass, and their results are listed in Table 1.

Yuanshantsu flood diversion tunnel is a 10m span tunnel excavated through weak rock formations of Miocene age. Three monitoring stations representing a folded rock and two typical rock conditions encountered at the project site were selected for back analysis, and the results are shown in Table 1.

Mingtan cavern consisted of 22.7m wide x 46.7m high x 158m long power cavern and 13.5m wide x 23.5m high x 172 m long transformer cavern is located in the rock formations of Waichecheng series of Oligocene in the Central Mountain Ranges of Taiwan. The rock strata encountered at the cavern site consist mainly of slightly metamorphosed, strong to very strong siltstone and sandstone. Three types of rock mass namely jointed sandstone, bedded sandstone and fault zone were identified at the cavern site. Cavern deformation measurement data obtained by the pre-installed extensometers in the roof and haunch areas were used for back analysis during construction. Results for the three types of representative rock mass are shown in the Table 1.

Tab 1　Information of case histories used in this study

Case No.	Project Name	Rock Type	Geological Age	σ_c(MPa)	RMR	D(GPa)
1	Hsuehshan Tunnel	Argillite	Oligocene	40	15	0.2
2	Hsuehshan Tunnel	Argillite	Oligocene	40	35	0.5
3	Hsuehshan Tunnel	Argillite	Oligocene	40	25	0.4
4	Hsuehshan Tunnel	Quartzite	Eocene	200	30	0.7
5	Hsuehshan Tunnel	Siltstone/Argillite	Oligocene	40	56	4.6
6	Hsuehshan Tunnel	Argillite	Oligocene	32	54	1
7	Hsuehshan Tunnel	Sandstone/Shale	Oligocene	39	50	1.2
8	Hsuehshan Tunnel	Shale/Sandstone	Miocene	39	73	3
9	Hsuehshan Tunnel	Sandstone/Shale	Miocene	39	45	6.2
10	Hsuehshan Tunnel	Sandstone	Miocene	68	77	9
11	Hsuehshan Tunnel	Sandstone	Miocene	68	69	7
12	Hsuehshan Tunnel	Sandstone	Oligocene	69	74	9.5
13	Hsuehshan Tunnel	Sandstone	Oligocene	69	74	9
14	Hsuehshan Tunnel	Argillite/Quartzite	Eocene	55	45	2.2
15	Hsuehshan Tunnel	Argillite/Quartzite	Eocene	55	35	2
16	Hsuehshan Tunnel	Quartzite	Eocene	164	79	12
17	Hsuehshan Tunnel	Argillite/Quartzite	Eocene	55	53	2
18	YuanShanTsu Flood Diversion Tunnel	Sandstone	Miocene	25	47	1.2
19	YuanShanTsu Flood Diversion Tunnel	Sandstone/Shale	Miocene	7	47	0.5
20	YuanShanTsu Flood Diversion Tunnel	Disturbed Zone	Miocene	5	36	0.3
21	Mingtan Cavern	Jointed Sandstone	Oligocene	150	69	6
22	Mingtan Cavern	Bedded Sandstone	Oligocene	100	58	5.5
23	Mingtan Cavern	Fault Zone	Oligocene	75	22	3
24	New Tienlun Cavern	Massive Sandstone	Oligocene	125	69	10
25	New Tienlun Cavern	Jointed Sandstone	Oligocene	125	50	7
26	Shilin Cavern	Massive Sandstone	Pliocene	25	65	1.8
27	Shilin Cavern	Massive Sandstone	Pliocene	25	70	3.2

New Tienlun cavern is horseshoe shaped with excavation dimensions of 22.6m wide x 41.4m high x 40.5m long. It is located in Paileng formation of Oligocene in the Central Mountain Ranges of Taiwan. The rock strata encountered at the cavern site consist mainly of slightly metamorphosed, very strong quartzitic sandstone and coarse grained massive sandstone. Two types of rock mass namely massive sandstone and jointed sandstone were identified, and the results of analysis are listed in Table 1.

Shilin cavern is also horseshoe shaped with excavation dimensions of 16.4m wide x 36.9m high x 51.6m long. It is located in the Kueichulin formation of Western Foothills of Pliocene age. The rock strata encountered at the cavern site consist mainly of weak to medium strong muddy sandstone and fine-grained sandstone. Two sets of monitoring data were obtained for back analysis and their results are shown in Table. 1.

PROPOSED EMPIRICAL RELATIONSHIP

In this study, totally 27 case histories of underground excavation were used. These case histories belong to 4 categories of rock strength, i.e., very strong rock (R5), strong rock (R4), medium strong rock (R3) and weak rock (R2) according to ISRM's rock strength classification. Plotting the data points of back analysis to the proposed trend shown in Fig. 4, the results are shown in Fig. 6. It may be seen that, generally speaking the results of back analysis agree quite well with those shown in Fig. 4 based on large volume of plate loading test data.

Based on the empirical relationship between deformation modulus and RMR value proposed herein, rock mass modulus with fair or better quality would depend strongly on the strength of rock material. For rock mass in the regime of poor to very poor quality, however, the modulus value appears to be less dependent on the strength of rock material and these relationships for various rock strengths merge into a narrow band as shown in Fig. 6.

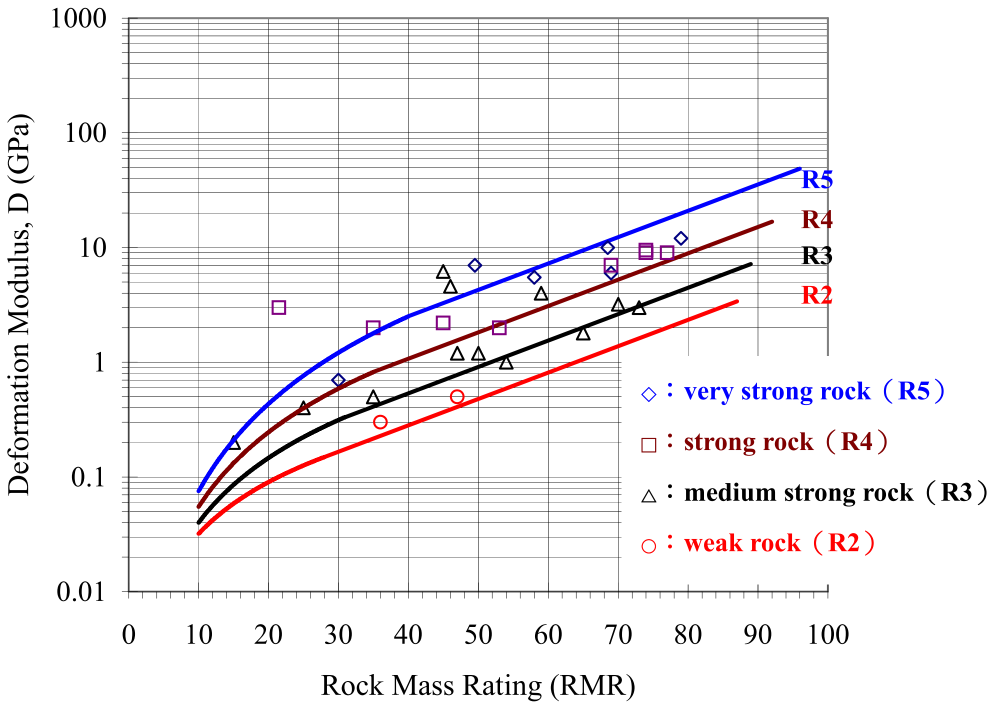

Fig. 6 Re-examination of empirical relationship by using results of back analysis of underground excavation case histories

CONCLUSION

An empirical relationship between deformation modulus and RMR rating of rock mass established by statistical study on large volume of plate loading test data and further re-examined by the results of back analysis in numerous underground excavation projects is proposed. The relationship shows that deformation modulus of rock mass with fair or better quality would depend strongly on the strength of rock material. For poor or very poor rock mass, the modulus would be dependent on the intact rock property due to the fact that the deformation behavior is dominated by the infill materials. This empirical relationship would provide a more reasonable estimation of the deformation modulus of rock mass than those most commonly used in engineering practice.

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