# Size and Stress Gradient Effects on the Modified Point Load Strengths of Saraburi Marble

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## Abstract

A modified point load (MPL) testing technique is proposed to correlate the results with the uniaxial compressive strength and tensile strength of intact rock. The test apparatus is similar to that of the conventional point load (CPL), except that the loading points are cut flat to have a circular cross-sectional area instead of using a half-spherical shape. Diameters of the loading point vary from 5, 10, 15, 20, 25, to 30 mm. This results in a new loading and boundary conditions on the rock specimens that mathematically allow correlating its results with those of the standard testing. To derive a new solution, finite element analyses and laboratory experiments have been carried out. For this early stage of development, the MPL specimens and models are taken as a circular disk. The simulation results suggest that the applied stress required to fail the MPL specimen increases logarithmically as the specimen thickness or diameter increases. The maximum tensile stress occurs directly below the loading area with a distance approximately equal to the loading diameter. The MPL tests, CPL tests, uniaxial compressive strength tests and Brazilian tensile strength tests have been performed. Over 400 specimens of Saraburi marble have been prepared and tested under a variety of diameter and thickness (or length). The uniaxial test results indicate that the strengths decrease with increasing length-to-diameter ratio. The Brazilian tensile strengths also decrease as the specimen diameters increase. Post-faulure observations on the specimens also suggest that shear failure is predominant when the specimen thickness is less than twice the loading diameter while extension failure is predominant when the specimens are thicker than three times the loading diameter. This can be postulated that the MPL strength can be correlated with the compressive strength when the MPL specimens are relatively thin, and should be an indicator of the tensile strength when the specimens are significantly larger than the diameter of the loading points. Even though both MPL and CPL tests overestimate the uniaxial compressive strength of the rock, the MPL results yield a better correlation than does the CPL strength index. The rock tensile strength predicted by the MPL testing is about twice the Brazilian tengile strength.

## 1. Introduction

Conventional point load (CPL) strength index has long been used as an indicator of the uniaxial compressive strength of intact rock for nearly three decades. In 1995, the test has become the ASTM standard test methods [1]. Several investigators have studied the correlation between the CPL strength index and the compressive strength of various rock types [2-12] in an attempt at understanding the true mechanism of failure under point loads and the effects of specimen sizes and shapes. The uncertainty of the relationship between CPL index and the compressive strength remains. It has been found that the compressive strength of rocks can vary from 6 to 105 times the CPL index, depending on the rock types [13, 14]. The ASTM standard procedure defines that the compressive strength can be calculated as 24 times the CPL strength index. This calculation is purely empirical, and hence often does not adequate, particularly in term of the reliability, when used in the analysis and design of geological structures. In addition the calculation of the CPL strength index does not have any theoretical support, and does not allow a transition correlation between the CPL index and the compressive or tensile strengths of the rock.

There is a drawback involving the CPL test configurations. The curved loading points (platens) have a certain disadvantage. The contact loading area can increase as the load increases (i.e., the spherical head sinking into the specimen surface). This is due to the deformation of the rock matrix. The definition of a singular loading point as used in the principle is therefore not strictly valid.

The objective of the present research is to develop a new testing technique, called “modified point load (MPL) test” to obtain a better indicator of the compressive and tensile strengths of intact rock. The effort involves laboratory tests and finite element analyses. A series of MPL testing, CPL testing, uniaxial compression testing and Brazilian tension testing are performed on cylindrical specimens with various sizes and shapes. Saraburi marble has been used as rock samples. The finite element analyses determine the stress distribution along the loaded axis of the MPL test specimens. Comparison is made between the predictive capability of the compressive strength by the CPL index and by the MPL results. Described herein are methods and results of the investigation.

## 2. Laboratory Testing

### 2.1 Modified Point Load Tests

The test configurations for the proposed MPL testing are similar to those of the conventional point load test, except that the loading points are cut flat to have a circular cross-sectional area instead of using a half-spherical shape. Several sizes of the loading point (platen) have been built in this research, i.e., loading diameters varying from 5, 10, 15, 20, 25, to 30 mm. Figure 1 compares the conventional loading point with the modified loading points having the diameters of 5 and 10 mm. The primary objective of having a flat loading surface is to ensure that the contact area between the steel platen and the rock surface remains constant as the load increases. The new loading and boundary conditions also allow a continuous transition between the uniaxial compressive strength test and the MPL results.

Saraburi marble has been selected for use as rock specimens due to its uniform texture and availability. For this early stage of development, the MPL specimens are taken as a circular disk. Figure 2 shows the loading and boundary conditions of the specimens. The specimen thickness (t) is varied from 5 mm to 40 mm. The specimen diameter (D) varies from 20 mm to 100 mm. Some of the prepared specimens are shown in Figure 3. The load is applied along the specimen axis, and is increased until the failure occurs. Figure 4 shows the arrangement for the MPL test. Digital displacement gauges with a precision up to 0.001 mm are used to monitor the deformation of the rock between the loading points as the load increases. Cyclic loading is performed on some specimens in an attempt at separating the elastic with the plastic deformation. This is primarily to detect the development of compressive failure (initiation of micro-cracks) underneath the loading points, as well as the corresponding applied stress [15]. The failure stress (P) is calculated by dividing the failure load by the contact area. Post-failure characteristics are observed and recorded.

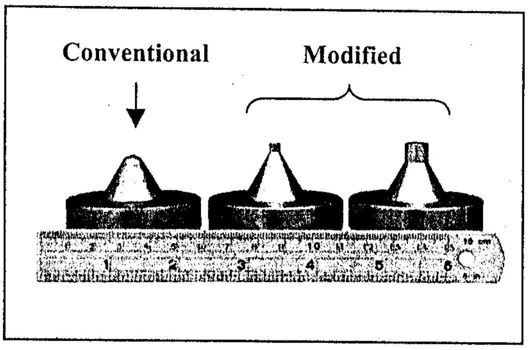

**Figure 1** Conventional and modified loading points.

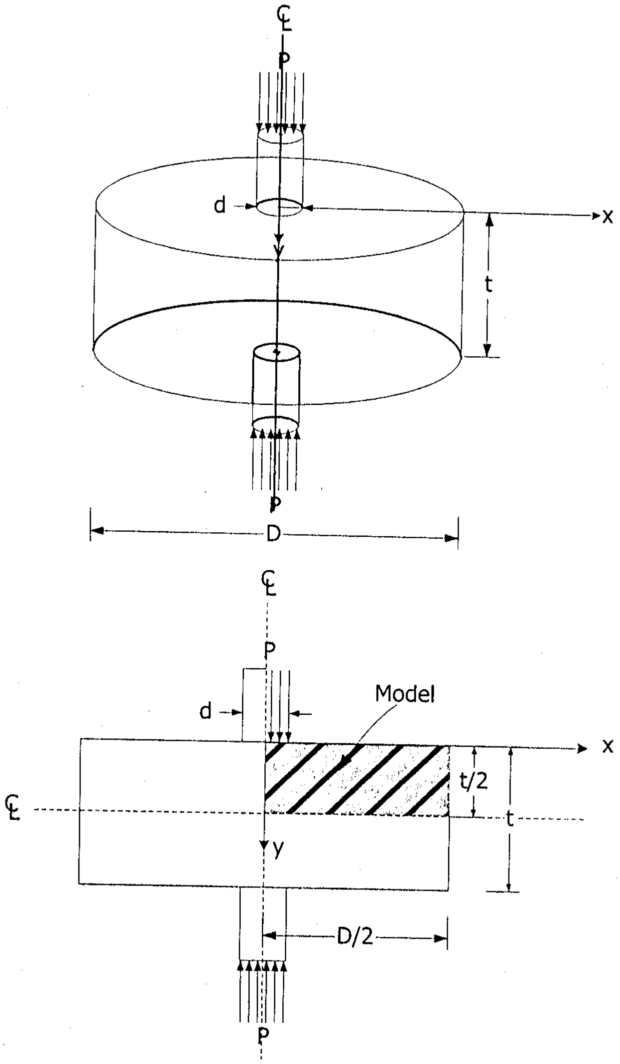

**Figure 2** Configurations of modified point load testing.

**Figure 3** Some marble specimens prepared for Testing.

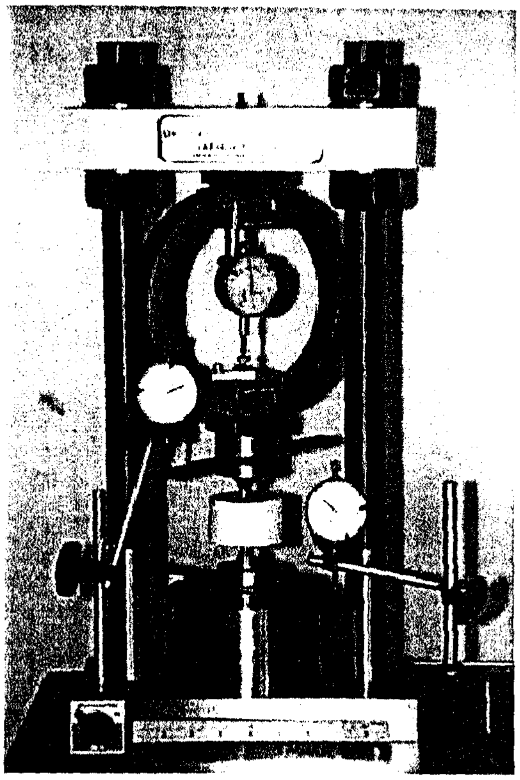

**Figure 4** Test arrangement for MPL testing.

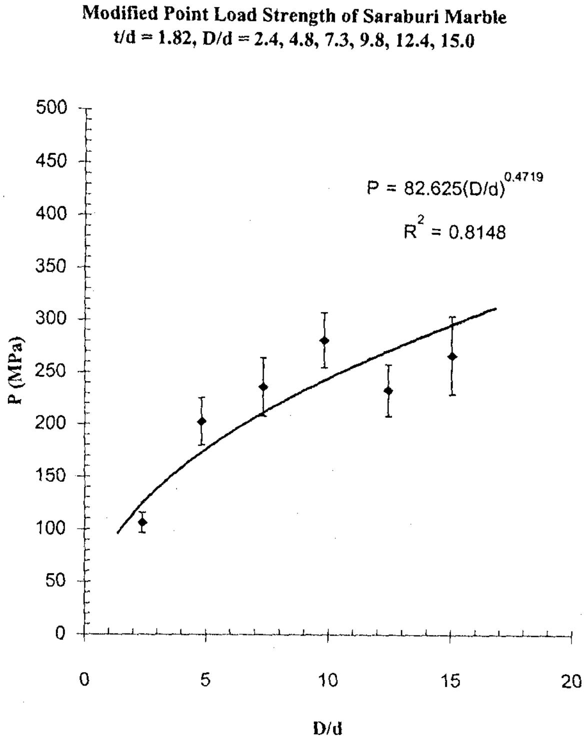

**Figure 5** MPL test results for t/d = 1.82.

Figures 5 and 6 show two sets of MPL results by plotting the failure stresses P as a function of specimen diameter and thickness, respectively. To isolate the effect of the loading diameter, the specimen diameter and thickness are normalized by the diameter of loading point (d), as shown in the figures. The stress P increases exponentially as D/d increases, which can be expressed by a power equation. The stress P tends to increase with the ratio t/d. The mathematical relationship between P and t/d remains uncertain. Post-tested observations on the specimens also suggest that shear failure is predominant when the specimen thickness is less than twice the loading diameter while extension failure is predominant when the specimens are thicker than three times the loading diameter. This implies that the MPL strength should be correlated with the compressive strength when the MPL specimens are relatively thin, and should be an indicator of the tensile strength when the specimens are significantly larger than the diameter of the loading points. Analysis and applications of the MPL test results will be discussed in section 4.

### 2.2 Uniaxial Compression Tests.

A series of uniaxial compressive strength tests have been conducted on Saraburi marble. The objective is to develop a data basis to compare with the MPL results via a new governing equation. The

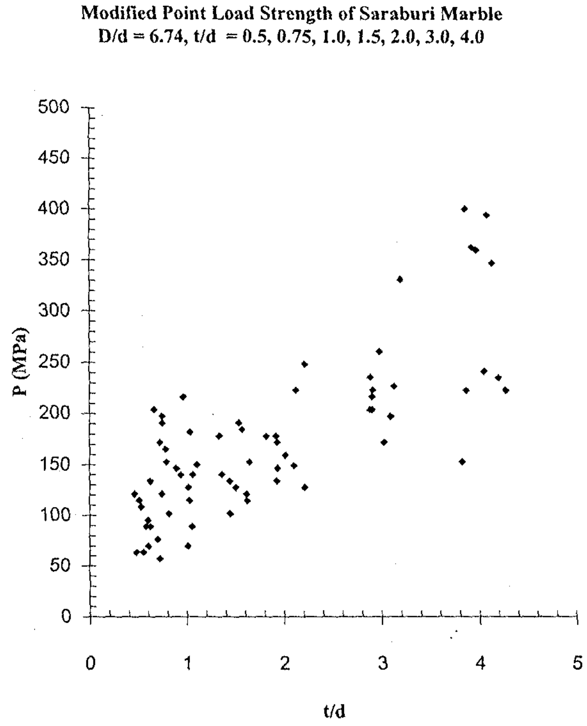

**Figure 6** MPL test results for D/d = 6.74.

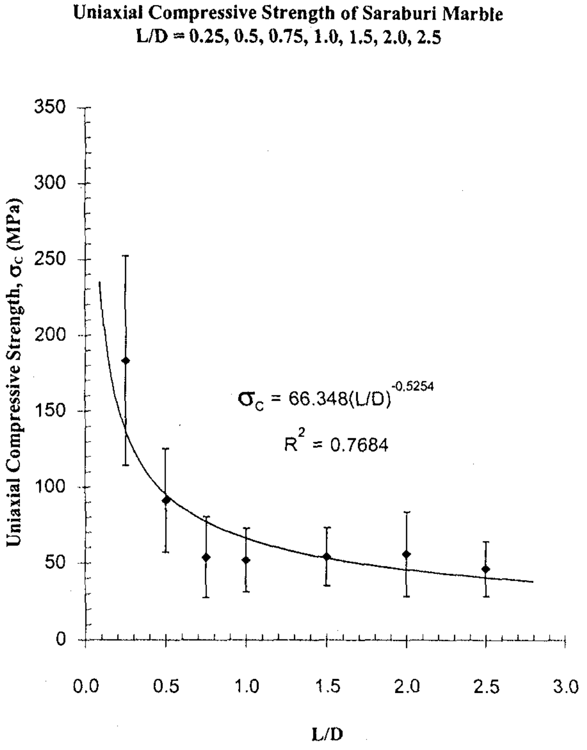

**Figure 7** Uniaxial compressive strengths of Saraburi marble.

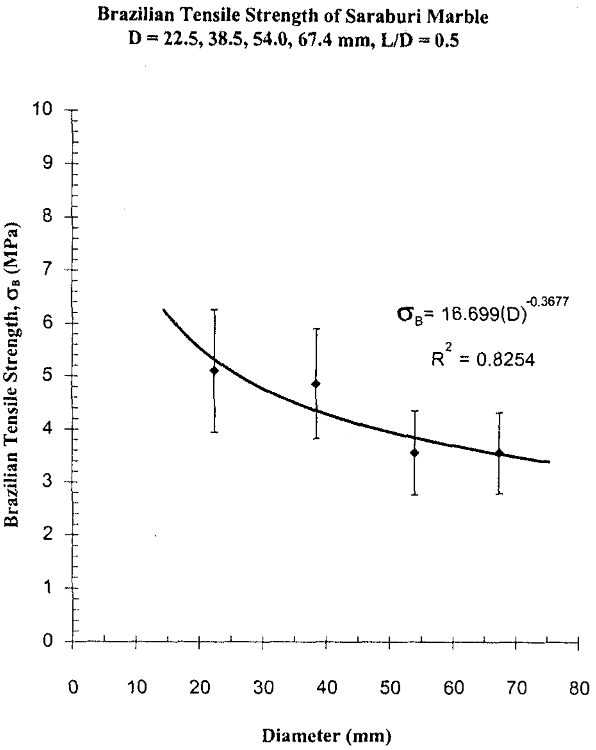

**Figure 8** Brazilian tensile strength of Saraburi marble.

sample preparation and test procedure follow the applicable ASTM standard [16] and ISRM suggested method [17], as much as practical. A total of 280 specimens have been tested under various sizes and shapes. The specimen diameters vary from 22.5, 38.5, 54.0, to 67.4 mm. The length-to-diameter ratio (L/D) varies from 0.25, 0.50, 0.75, 1.0, 1.5, 2.0, to 2.5. All specimens are loaded to failure under a constant loading rate. Post-failure characteristics are observed.

Figure 7 plots the compressive strength as a function of L/D ratio. The results clearly show the end effects of the specimen on the strength values. The strength decreases as the L/D increases. The strength results have not shown the effect of the specimen size. This is probably due to the fact that the size effect pronounces more in tensile failure than does in compressive shear failure. Short specimens (L/D lower than two) tend to fail under the compressive shear failure mode. Extension failure dominates when the L/D ratios are larger than two. In general this finding agrees reasonably well with similar experiments obtained elsewhere [18-23].

### 2.3 Brazilian Tension Tests

To determine the relationship between the MPL strength and the tensile strength, a series of Brazilian (indirect) tension tests have been performed on the Saraburi marble. The sample preparation and test procedure have followed the applicable ASTM standards [24], as much as practical. Forty specimens have been tested. They have a constant L/D ratio = 0.5, while the specimen diameters vary from 22.5, 38.5, 54.0, to 67.4 mm. The tensile strength tends to decrease as the specimen size increases, and can be expressed by a power equation (Figure 8). This finding agrees with those obtained from similar experiment [25].

### 2.4 Conventional Point Load Tests

The conventional point load (CPL) testing is performed on Saraburi marble to obtain a base line information. The results will be compared in term of the predictive capability with that of the MPL test. The test procedure follows the applicable ASTM standard [1]. The specimen diameter is maintained constant at 67.4 mm. The thickness varies from 5.0 to 40.0 mm. A total of 70 specimens have been tested. The CPL strength index is calculated by dividing the failure load by the specimen thickness and diameter. It seems to be independent of the specimen dimensions. The point load strength index is averaged as 4.5 MPa.

## 3. Finite Element Analyses

A series of finite element analyses have been carried out to compute the stress distribution along the loaded axis of MPL specimens as affected by the specimen diameter and thickness. The results will be used to correlate with the compressive and tensile

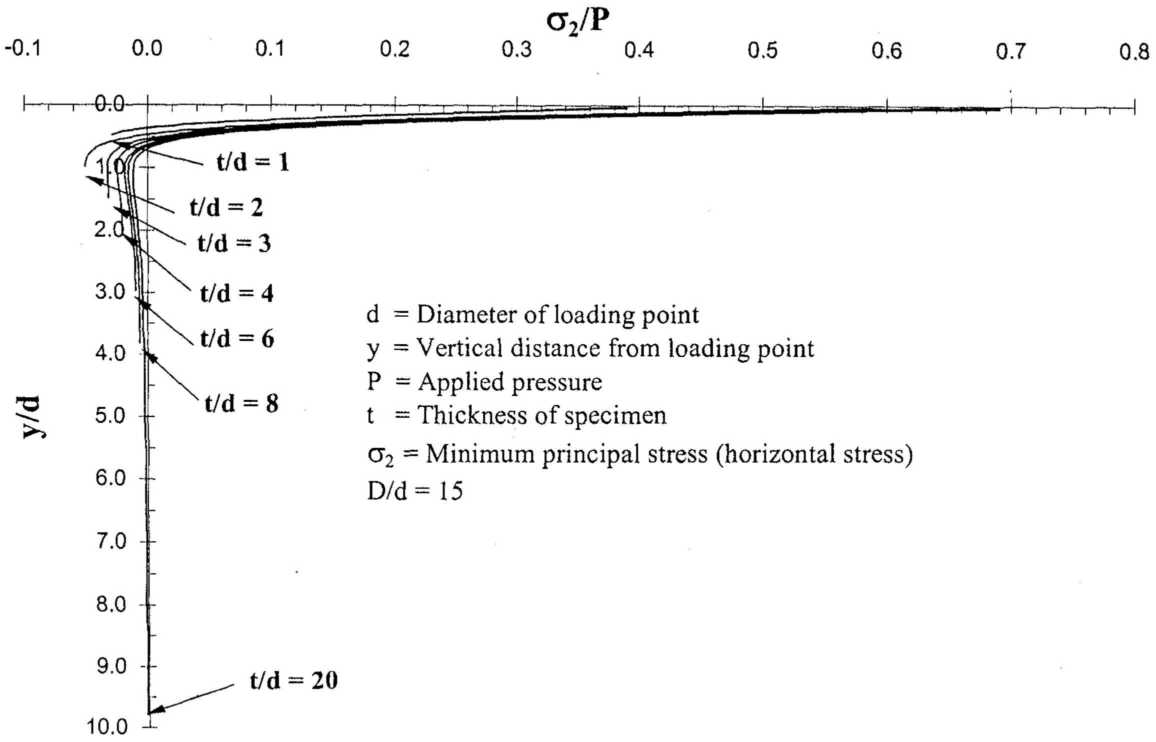

**Figure 9** Distribution of the minimum principal stresses along the loaded axis of MPL specimens.

strengths obtained from the standard test methods. Due to the two symmetry planes, only one-fourth of the specimen has been modeled (Figure 2). The analysis is made in axisymmetric, assuming that the material is linearly elastic. A finite element code GEO [26, 27] is used in the simulations. For all models the elastic parameters of the marble are maintained constant. They are obtained from the uniaxial compression test. The elastic modulus is defined as 6.75 GPa, and the Poisson's ratio as 0.25. The specimen diameter (D) and thickness (t) have been varied within the range used in the laboratory experiment, and subsequently their effects on the stress distribution can be assessed. To isolate the impact from the size of loading point, D and t are normalized by the loading diameter (d).

Figure 9 plots the minimum principal stresses ($\sigma_2$) along the loaded axis for MPL specimen models with a constant D/d ratio but t/d ratio varying from 1 to 20. These stresses are normal to the loaded axis. It is clearly shown that the largest tensile stress is developed near the loading area. This point should also be the point where the extension failure initiates. Similar findings have been reported by Wei et al. [13] for the CPL test specimens. For the t/d is equal or larger than two the magnitude of the largest tensile stress decreases as increasing the t/d ratio. For t/d equals one (very thin specimens), the largest tensile stress decreases. For this case most of the stresses induced along the loaded axis are in compression. This indicates that thin specimens tend to fail under compressive shear failure while thick specimens fail under extension failure. This also agrees with the post-failure observations on the MPL specimens.

The results obtained from two series of computer simulations are shown in Figures 10 and 11. The applied stress (P) is normalized by the largest values of the tensile stress ($\sigma_2$), and are plotted as a function of t/d and D/d. The P/$\sigma_2$ ratio in Figure 10 is obtained from a constant D/d = 15. The results shown in Figure 11 is obtained from the simulations with a constant t/d = 2.5. The stress ratio P/$\sigma_2$ increases logarithmically with t/d and with D/d. These curves can be used to correlate the MPL results with the uniaxial compressive strength and tensile strength of the rock.

## 4. Comparisons of the Strength Results

The predictive capability of the CPL and MPL test results can be assessed. The results are used to determine the uniaxial compressive strength of the marble. The actual compressive strength of the marble specimen for L/D ratio = 2.5 (satisfy both ASTM and ISRM) can be calculated from Figure 7 as 41 MPa.

Using the ASTM recommended calculation, the CPL strength index determines the uniaxial compressive strength of marble as 108 MPa (24 x 4.5 MPa).

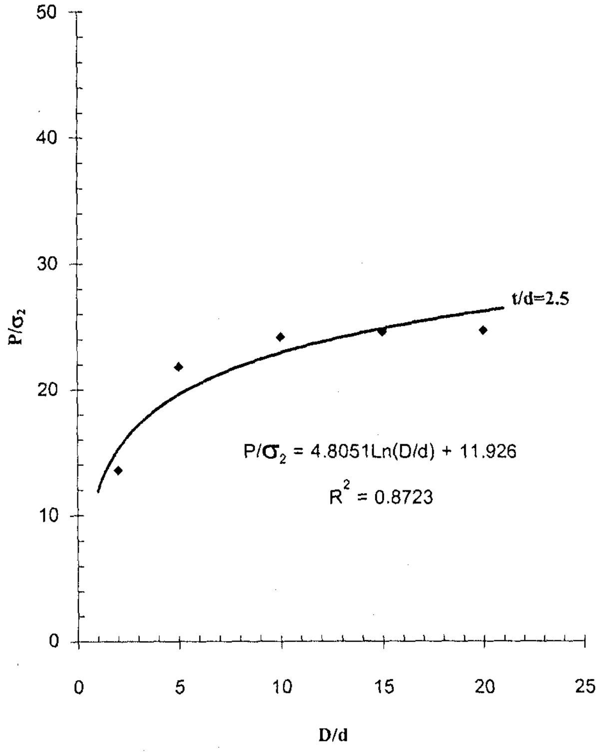

**Figure 10** Normalized failure stress as a function of D/d, obtained from numerical analysis.

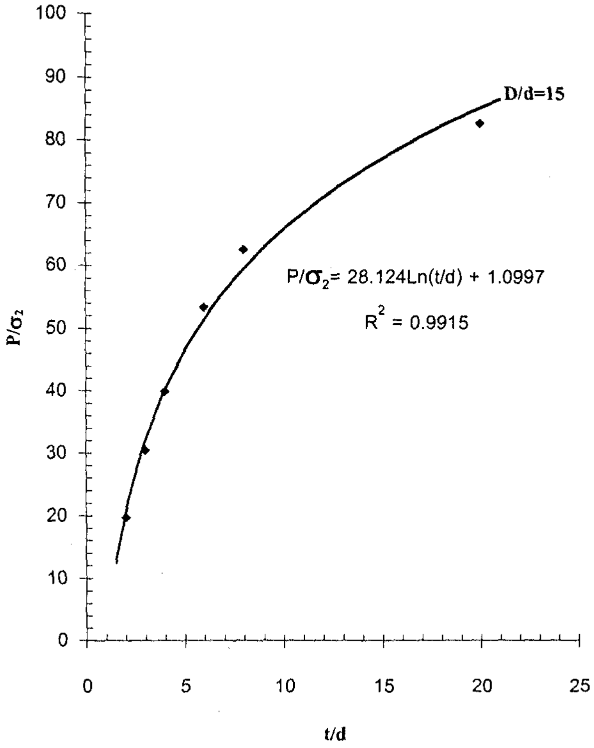

**Figure 11** Normalized failure stress as a function of t/d, obtained from numerical analysis.

Extrapolation of the MPL test result shown in Figure 5 for the failure stress at D/d = 1.0 (uniaxial test condition) yields the uniaxial compressive strength of the marble as 83 MPa. This value can be compared with the uniaxial compressive strength at L/D = 1.8, because the MPL results are from t/d = 1.8. The actual compressive strength at L/D = 1.8 is 48 MPa (calculated from Figure 7).

It can be clearly seen that the CPL test overestimates the actual strength by a factor of 2.6 (or 108/41). The MPL test overestimates the actual strength by a factor of 1.7 (or 83/48). Since the MPL prediction is based on the actual distribution of the strength data, it is more reliable. The discrepancy is probably due to the non-uniformity of the mechanical response among the marble specimens.

The CPL strength index can not determine the tensile strength of the marble. The MPL results can determine the rock tensile strength by using the relationship given in Figure 11. At D/d = 10 the stress ratio $P/\sigma_2 = 26.4$. The D/d = 10 is selected because under this dimension ratio the rock fails in tension mode. Extrapolation of the logarithmic curve in Figure 5 gives the value of P from the experiment equals to 245 MPa. The $\sigma_2$ value is calculated as 9.27 MPa. This is the largest tensile stress induced in the specimen at failure, and hence represents the tensile strength of the marble. The tensile strength predicted from MPL test can not be compared with the Brazilian tensile strength because their loading configurations are different.

## 5. Discussions

Intrinsic variability or the mechanical non-uniformity among the marble specimens poses some difficulties, particularly in the correlation process. The standard deviations from various tests are relatively high, e.g. 10–20%. Even though the rock appears to be uniform and homogeneous, the variability might be caused by the relatively large grain (crystal) sizes of the marble, as compared with the loading areas. This could cause the discrepancy between the prediction and the actual strength results.

Despite the intrinsic variability of the marble, the proposed MPL test is a promising method of predicting the compressive strength of the rock. More MPL test data are needed to further define the effects of the specimen thickness (t/d) and diameter (D/d). Additional computer simulations are desirable to obtain the variation of MPL results under a wider range of specimen dimensions. Verification of the proposed concept with different rock types is also desirable.

## 6. Conclusions

The objective of the present research is to develop a new testing technique, called "modified point load (MPL) test" to obtain a better indicator of the compressive and tensile strengths of intact rock. The effort involves laboratory tests and finite element analyses. A series of MPL testing, CPL testing, uniaxial compression testing and Brazilian tension testing are performed on cylindrical specimens with various sizes and shapes. Saraburi marble has been used as rock samples. The finite element analyses determine the stress distribution along the loaded axis of the MPL test specimens. Comparison is made between the predictive capability of the compressive strength by the CPL index and by the MPL results.

The uniaxial test results indicate that the strengths decrease with increasing length-to-diameter ratio. A power law can be used to describe their relationship. The effect of specimen size on the uniaxial compressive strength is obscured by the intrinsic variability of the marble. The Brazilian tensile strengths also decrease as the specimen diameters increase. The results from MPL test agree well with those from the finite element analyses. This confirms that the logarithmic relations of stress and specimen shape derived by a series of numerical analyses can be used to correlate the MPL strength with the uniaxial compressive strength of the intact rock. Post-tested observations on the specimens also suggest that shear failure is predominant when the specimen thickness is less than twice the loading diameter while extension failure (fracture) is predominant when the specimens are thicker than three times the loading diameter. This can be postulated that the MPL strength can be correlated with the compressive strength when the MPL specimens are relatively thin, and should be an indicator of the tensile strength when the specimens are significantly larger than the diameter of the loading points. The MPL results correlate with the uniaxial compressive strength of the rock better than does the CPL strength index. Discrepancy remains between the predictions from both methods and the actual compressive strength data. More MPL test data are needed to further redefine the effects of the specimen thickness (t/d) and diameter (D/d). Additional computer simulations are desirable to obtain the variation of MPL results under a wider range of specimen dimensions.

## 7. Nomenclature

$\sigma_2$ = Minimum principal stress
D = Specimen diameter
d = Point load diameter
P = Applied stress for MPL testing
t = Specimen thickness
x = Horizontal distance from loading point
y = Vertical distance from loading point

## 8. Acknowledgments

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