Some pitfalls and misuses of rock mass classification systems for mine design

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Synopsis

Rock mass classification systems are extensively used in rock engineering design work, and mine design is no exception. Among the systems most widely used for mining-related design work are the NGI Q-system (Barton *et al.*, 1974), the RMR system (Bieniawski, 1976), the MRMR system (Laubscher and Taylor, 1976) and, more recently, the GSI system (Hoek *et al.*, 1998).

Classifying the rock mass is widely seen as being the fieldwork required to characterize the rock mass and enable the application of empirical design methods associated with the different classification systems. This paper argues that it is fundamentally important to recognize the distinction between rock mass characterization and rock mass classification. These two processes should, in most cases, be separated from each other. Rock mass characterization should be used to determine the intrinsic properties of the rock mass independently of the application; i.e. independent from the infrastructure to be designed, the size, shape, and orientation of the excavation(s) or pillar(s), etc. Rock mass characterization should also be compatible with most classification systems and empirical design methods to be used. Rock mass characterization is the background fieldwork required to perform rock mass classification and/or engineering design work.

Rock mass classification is the subsequent step to the characterization, and an integral part of the design process. Parameters that vary according to the design, such as the relative orientation of geological structures compared to the opening or the mine-induced stresses, should be calculated as part of the rock mass classification and design process, rather than during the rock mass characterization process.

The failure to distinguish between rock mass characterization and rock mass classification can lead to major design errors and poor results.

Keywords
rock mass, classification, characterization, rock engineering, mine design.

Introduction

The rock mass comprising the intact, altered solids and the defects with or without infill and variable orientation, scale, and shape is one of the most complicated engineering construction materials. Unlike commonly used man-made engineering materials such as steel and concrete, which have controlled specifications, the *in situ* rock mass is a natural matter and the result of complex geological processes. It therefore has a very variable material composition, in space and in time. It also exhibits intricate behaviours when subjected to different loading conditions.

The need for rock mass classification systems originally arose from the requirement that rock engineers who were involved in design had to relate experiences gained at different sites with different ground conditions and ground support, and apply them to new projects (Hoek and Brown, 1980).

As the classification schemes developed and their application in civil and mining engineering spread, they became increasingly used to *'... build up a picture of the composition and characteristics of a rock mass to provide estimates of the strength and deformation properties of the rock mass'* (Hoek *et al.*, 1995).

The two classification systems that emerged from the 1970s and became widely used for mining-related design work were the NGI Q-system (Barton *et al.*, 1974) and the RMR system (Bieniawski, 1974, 1976). Their popularity resulted from their useful application to a number of widely used empirical design techniques relevant, for example, to caving mines (Laubscher and Taylor, 1976), to open stope mines (Mathews *et al.*, 1981; Potvin, 1988), and generally to ground support design (Grimstad and Barton, 1993). Classification systems have also been used to derive input parameters for the use of failure criteria, or elastic properties in numerical models. For example, relationships

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between classification values and the friction angle 'ϕ' and the cohesion '*c*' enable the use of the Mohr–Coulomb failure criterion (Bieniawski, 1989; Milne, 2007). More recently, the GSI system (Hoek *et al*., 1998) was devised to provide input (*m* and *s* values) into the Hoek and Brown failure criterion (Hoek and Brown, 1980), as it is often used in the modern proliferation of numerical modelling techniques.

Many of these empirical design methods are particularly well suited for 'greenfield' and 'brownfield' feasibility studies where the target level of accuracy is generally within 20 to 30 per cent. At the same time, there is a critical need for these methods to be robust in terms of giving design answers which are 'in the ballpark' and, therefore, minimize the risks of providing a wrong answer. At a mining project conception stage, a successful 'ballpark' estimate will ensure that the real value of projects can be created, while a wrong design would destroy the value of most projects.

The robustness of these empirical design methods is highly dependent on the proper use of the appropriate rock mass classification systems. Whether a classification system and empirical design is appropriate or not will be dictated by the critical failure mechanism. If the classification of the rock mass input into the empirical design method is adequate, then the design will likely achieve the feasibility study accuracy requirements.

There are many sources of inaccuracy and uncertainty inherent to the use of rock mass classification. Many of them will be discussed in this paper, with an emphasis on some of the most common traps and misuses of these systems, which can lead to very poor design outcomes.

Differentiation between rock mass classification and rock mass characterization

Classifying rock masses is widely seen as being the fieldwork required to characterize the rock mass and enable the application of empirical design methods associated with the different classification systems. This perhaps is the result of the original purpose of the classification systems, which was to: *'...give a quick and repeatable assessment of the rock mass to provide guidelines for underground opening stability and support requirements'* (Milne, 2007). In the context of empirical design, which is often performed by consultants with a limited amount of time for gathering data underground or from drill core, it becomes an attractive proposition to use classification techniques to replace the more labour-intensive and detailed work of characterizing the rock mass.

However, it is fundamentally important to make a distinction between rock mass characterization and rock mass classification. These two processes should in fact be separated from each other.

Rock mass characterization should be used to determine the intrinsic properties of the rock mass, independently of the application, i.e. independently of design method or the infrastructure to be designed and the size and shape of the excavation(s) or pillar(s).

Rock mass characterization should be generic in nature, capturing the basic input parameters that can be used in classification systems and empirical design methods. Rock mass characterization is the background fieldwork required to perform rock mass classification. It should concentrate on measurements and information about the intact rock strength, the intensity of natural fractures in the rock mass, and the conditions of these fractures. It should, however, not be limited to obtaining parameters used in the classification systems. The characterization should also aim to provide a context or framework for further design decisions and the use of rock mass classification systems.

Rock mass classification is the subsequent step to the characterization. Parameters that vary according to the design, such as the relative orientation of geological structures compared to the opening or the pillar, the induced stresses, the groundwater, etc., should be calculated as part of the rock mass classification and design process, rather than during the rock mass characterization process.

If one considers a uniform volume of rock mass, this volume will have a unique rock mass characterization, but at the same time, it can have multiple rock mass classification values depending on what is being designed, the orientation of the designed structures (slope, stope, drive, pillar, etc.), and the scale of these features. If the design/scale changes, the classification value can change despite the fact that the rock mass considered is exactly the same.

This is a true reflection of the anisotropic behaviour of most rock masses and the inability of the classification systems to account for it (Hadjigeorgiou and Harrison, 2011). Let us look at an example that clearly illustrates this important concept. A rock mass forming a small hill near Alice Springs in Australia has a prominent continuous bedding joint set with weak joint conditions (say smooth and planar with slippery alteration) dipping towards the right end and identified as joint A on the photo (Figure 1). It also has a cross-bedding joint set (identified as joint B), not very continuous and with strong joint conditions (say rough and undulating with no alteration).

When one considers a slope design on the right side of the picture, joint set A is the critical set and the joint condition of joint set A would be considered to obtain a classification rating. If the Q system was used, the shear strength factor *Jr/Ja* for this rock mass would be 1/4 (0.25). The reader is referred to Appendix A for more details on the Q system and relevant parameters. When considering the slope on the left side, joint set A no longer influences the stability of the left slope and joint B is the discontinuity that is critical to stability, and as such, joint B's properties should be used in the classification. The *Jr/Ja* value for the left slope would be 3/0.75 (4). Given that the other factors (*RQD*, *Jn*, *Jw*, and *SRF*) remain the same in both cases, the *Q* value for the slope on the left is 16 times higher than the one on the right (0.25/4), but this is exactly the same rock mass. It is interesting to observe that the natural slope on the left is much steeper than the one on right side, a good reflection of the difference in the *Q* rating and of the anisotropic behaviour of this rock mass.

This example brings to light the fact that while classifying rock masses, one has to choose which joint set property is to be used to characterize the joint condition for the designed structure under consideration. When the classification exercise is made without a design in mind, often the most prominent or weakest joint set is used. However, selecting the most prominent joint set may not be relevant to a specific design, i.e. joint set A in the left slope in Figure 1. Divorcing classification from the design can lead to design outcomes

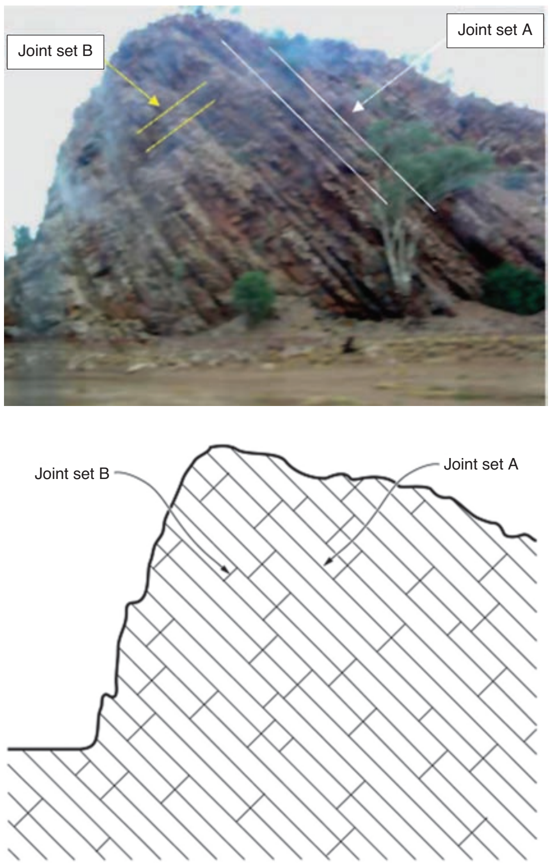

Figure 1—Example of a rock mass that has a very different classification value when considering the slope stability on the left and right sides

that are considerably over- or under-conservative, depending on the case, and this is why the classification is part of the design process rather than a replacement of a rock mass characterization process. It is logical to select the joint condition of the set that is critical to the designed structure for classification purpose.

In other cases, the *Q* value could also be influenced by the *SRF* factor when, for example, the volume of rock mass under consideration is located in a highly stressed pillar compared to a de-stressed hangingwall. Another example could be when using the RMR system, where the prominent joints are oriented favourably in one design option compared to an unfavourable orientation in another. In this case, the *RMR* of a volume of rock in the wall of a north–south drive would be very different than the same volume of rock in the wall of an east–west drive.

It is permissible for a designer to skip the rock mass characterization process and perform a classification directly, if the purpose is to complete a specific design. However, this classification data should not be used in the future for other design work, unless the data is verified and, if necessary, adjusted according to the new design. This, in the authors' experience, is a very common mistake as frequently classification values are borrowed from previous design work and applied to a new design. Another common mistake observed at mine sites is for staff to perform 'generic' rock mass classification work, with no specific design in mind, often using the joint conditions of the most prominent or weakest joint set. As mentioned before, this is likely to produce over- or under-conservative designs, and possibly with accuracy outside of the required 'ballpark' estimate. In such cases, rock mass characterization work should be performed instead of using a classification generically, with no immediate design in mind. The situation is exacerbated if the anisotropy and larger-scale inhomogeneity are ignored when the rock mass is modelled using geostatistical methods available in mine planning packages. More details on rock mass characterization are given in the following section.

Rock mass characterization

As mentioned before, the rock mass characterization process should be independent of the design process and, as a result, a given rock mass volume has a unique rock mass characterization. Rock mass characterization is not based entirely on quantitative measurements or qualitative observations, but on a combination of both. Rock mass characterization focuses on characterizing the intact rock properties, the intensity, orientation, and persistence characteristics of natural fractures (joint sets), and the conditions of each joint set. It should contain all information necessary to enable future 'desktop' classification of the rock mass, using any of the popular classification systems. Sound rock mass characterization should provide information on the rock mass character at different scales. For example, bench- or tunnel-scale characterization may ignore the larger-scale structures that are spaced at intervals that are greater than bench/tunnel scale. Such structures may have a large impact on the design but are not represented appropriately in the rock mass classification systems.

The intact rock property of interest here is the unconfined compressive strength, which can be obtained from laboratory tests, point load tests or, if low accuracy is deemed acceptable, from simple means field tests to determine rock strength classes (British Standard (BS 5930, 1981) or the Approximate Intact Rock Strength (Robertson *et al*., 1987).

Joint mapping is required to identify all joint sets, their dip, and their orientation. For each of the joint sets, the joint condition must be recorded qualitatively using terms compatible with classification systems, such as:

- Small scale roughness (slickensided – smooth – rough)
- Large scale roughness (planar – undulating)
- Weathering (from unweathered to highly weathered)
- Alteration and infilling (description (soft strong, low friction) of the infill material, and the thickness of infill)
- Aperture of joints
- Other.

The intensity of fracturing is generally captured using RQD, which is orientation-dependent if taken from drill core. It is also good practice to use an alternative technique such as fracture frequency in addition to RQD, to overcome some of the well known shortcomings of this method. Furthermore, the collection of the mean joint spacing of each joint set can also be used to estimate RQD (Hutchinson and Diederichs, 1996, p. 184). Some versions of the RMR system use all of the above three parameters.

Rock mass classification systems ignore the influence of intact rock bridging between fractures and do not in any way account for this phenomenon. Figure 2 (Brown, 2003) illustrates how the failure to incorporate rock bridges could lead to a misrepresentation of the rock mass. The two rock masses displayed will behave quite differently under different loading conditions. For this reason, the information on the rock bridging will impact on the design. It is our opinion that, at the least, qualitative information on the bridging characteristics of the rock mass should be included in the rock mass characterization. In this regard, structural geological knowledge will add value to the rock mass characterization by enabling an understanding of the cross-cutting nature of the different joint sets in the rock mass. In the slope example presented previously, bridging would be expected on the left side while it may not exist along the bedding planes on the right side. This could be resolved if a comprehensive structural model was available to the designer using a technique like tectogenesis (Dight and Bogacz, 2009).

Rock bridging is difficult to quantify, but some attempts have been made to quantitatively describe it and quantify its influence (Brown, 2003; Elmo *et al*., 2007).

The benefit of having a good rock mass characterization is that any empirical design method can be applied no matter which classification system it is based on. Any type of rock mass classification work can be performed using this data.

The literature contains techniques to convert values from one classification to another ($RMR = 9 \ln Q + 44$, after Bieniawski, 1976) or ($RMR = 15 \log Q + 50$, after Barton, 1995), but these conversions, which have been criticized as being unreliable due to the wide scatter of comparative data, or erroneous because the classification systems rely on different parameters with different weightings (Milne, 2007; Hadjigeorgiou and Harrison, 2011), are no longer necessary when a good rock mass characterization exists. Each classification system can be applied independently based on the same raw data.

It is interesting to note that the GSI system, which was briefly introduced in the previous section, can be seen as an attempt to bridge the rock mass classification and characterization processes.

However, there appears to be some confusion in the literature as to the way it should be applied. Mostyn and Douglas (2000) suggest it should be interpreted to the scale of the structure being designed, while Cai *et al*. (2004) have interpreted the GSI on a fixed scale. Using the GSI in the way suggested by Mostyn and Douglas, it becomes a classification system, dependent on the design.

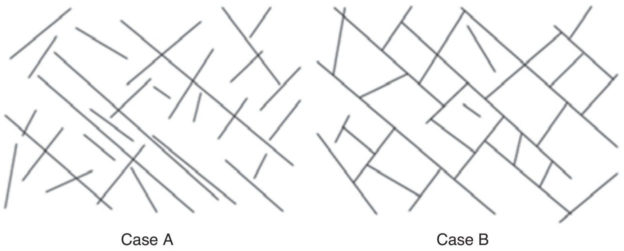

Figure 2–Illustration of the influence of rock bridging on the rock mass (Brown, 2003)

The GSI system is sometimes used to classify the rock mass, independent of the design, assuming a fixed scale as suggested by Cai *et al.* (2004). The GSI relies on a matrix describing the joint intensity on the vertical axis and the joint condition on the horizontal axis and, as such, ignores the complexity of rock masses by reducing it to a combination of a single joint intensity and a single joint condition parameter. As such it is limited in its ability to fully classify the rock mass. Because of its simplicity, it implicitly assumes that the rock mass under consideration is homogenous and isotropic. Both these assumptions can easily lead to erroneous designs and will have to be applied with caution in design methods.

The authors have seen a tendency over the last couple of years to classify and even to characterize the rock mass in terms of GSI only. The driving force behind this, of course, is the ease with which the GSI value can be turned into strength parameters for numerical analysis. The GSI is a valuable addition to the rock engineers' toolbox, but its use as a primary characterization or classification tool will lead to erroneous designs due to its inadequacy in capturing all the relevant design considerations.

Inaccuracy of rock mass classification systems

Most people that have used rock mass classification systems realize that they are not meant to be precise and accurate. *'Since we are engineers and not scientists, our craft is the ability to make realistic approximations, leaving unnecessary decimal places on the calculator'* (Barton, 2007).

The original intent of classification was to provide a 'quick' estimation of rock mass properties to enable the transfer of design experience from one site to another. When applied to empirical design methods, the authors believe that the goal of classification method should be to assess the rock mass competency, within the correct class of rock mass, i.e. poor – fair – good – very good, in order to achieve a sound 'ballpark' design. This design can then be refined and optimized in the future. To optimize the design, it may be necessary to obtain additional data from more rock mass exposures, revert back to the rock mass characterization, use more sophisticated design tools, or gain early experience with the rock mass response to mining, using an instrumentation programme.

To apply a rock mass classification (and, to a lesser extent, rock mass characterization), requires a certain amount of interpretation and, therefore, there are uncertainties in the application of the methods. Classification methods also have deficiencies in the way they aim at representing a material as complex as a rock mass. Although, with proper training, the above potential sources of error can be contained to a manageable level and the classification can provide a representative and reproducible result (within the correct rock mass class), it is worth explaining some of the common sources of inaccuracies and uncertainty.

Since the application of rock mass classification systems has been extended from small-scale civil tunnelling engineering (e.g. the Q-system) to large mining structures (applications such as stope design, block caving mine design, and slope design), an issue related to the difference in scale has arisen.

For example, Barton (2007) suggests that Q-system should be applied on a round-by-round basis; *'In principle, one needs to design support (or select the correct support class) by classifying each round as the permanent mining drift or decline is driven. This is also a familiar task in civil engineering tunnels'*.

If one uses the same Q-system as an input for open stope design, using for example the stability graph method (Potvin, 1988), a round–by-round classification could mean 10 or perhaps 15 values of Q', for designing a single stope wall. Then one could average these values, or take the lowest value to be conservative, or give a range of values, but a decision of a unique Q' value will need to be taken sooner or later in the process, as only one wall dimension can be constructed for a given stope plane. There are sources of error and uncertainty with all of these options. The authors' preferred approach would be to use engineering judgement to select the most 'representative' Q' value for the wall, but this requires experience. Therefore, previous design experience is one obvious requirement to control the error and uncertainty in applying rock mass classification for design.

Unfortunately, it is often the less-experienced employees that are assigned the time-consuming task involving the fieldwork, and they are most often not likely to be the ones performing the design work. Since much less interpretation is required in performing rock mass characterization (which, once again, is not linked to the design) than classification, this becomes another strong argument in favour of using characterization as a prior step to classification.

Experience also provides a significant advantage to assessing each parameter in the classification system with the required accuracy. Distinguishing between a rough and smooth joint surface, for example, can be difficult. It is important, however, as the origin of the structure (rough suggests extension, smooth suggests fabric-like bedding or a shear origin), gives a hint to continuity and influence in the characterization. Even assessing quantitative parameters such as RQD can be the source of large errors due to blast damage in the case of mapping or core damage in the case of core logging, the influence of the relative orientation of the face or core, etc. The RQD is also dependent on the technique used to estimate it. It is the authors' experience that the correlation of RQD obtained from core logging, underground line mapping, window mapping, or the volumetric joint count ($RQD = 115 - 3.3Jv$, after Palmström, 1982) is often poor and can lead to a wide range of results.

The issue of scale or representative rock volume has already been raised, but it can also influence which joints should be considered in the classification or left as insignificant. A joint with a short trace length (say less than 1 m) could be significant at the tunnel scale, but insignificant at the stope wall or open pit slope scale. Also, a joint can be classified as random at the tunnel scale, because its spacing is so large that it is observed only randomly in a tunnel, but can become a joint set at the stope wall or open pit slope scale.

In underground mine applications, one easy way to perform a 'reality check' on the classification value obtained by systematically assessing all parameters is to observe the shape of the drive in which the work is being done. An erratic profile is a reliable telltale of poor ground conditions, while a perfect 'as-designed' profile indicates that the ground condition is likely to be good. This provides a first assessment on which side of the 'fair' class the classification rating should be (less than fair implies $Q < 4$ and RMR < 40, or better than fair $Q > 10$ or RMR > 60). A quick observation of joint spacing (small or large) and the presence (or not) of slippery material on joints is also another quick indicator on which side of the 'fair' class the rock mass is likely to be.

It is the authors' experience that the application of classification systems can be taught to inexperienced engineers and geologists, and representative and reproducible results can be obtained. It requires some training and practice, and an awareness of the pitfalls and inaccuracies outlined in this paper. The reason for this is that the rock mass classification is performed by the application of fixed systems. For the most part, rock mass characterizations can also rely on predefined description schemes. However, as the characterization should also include relevant information that is not covered by predefined systems, sound rock mass characterization requires some experience.

Summary and conclusion

Empirical design methods based on rock mass classification systems are the methods of choice at mining project conception. They can provide robust designs despite their inherent low accuracy. However, the designs will be robust only if the main source of input, the rock mass classification data, is applied correctly.

There are many potential pitfalls to be avoided and sources of uncertainty to be controlled when applying rock mass classification methods. Firstly, it is critical to understand the difference between rock mass characterization and rock mass classification. Rock mass characterization is the prior step to classification and it is independent of the rock engineering structure(s) to be designed. For any given volume of rock, there is a unique rock mass characterization. The rock mass characterization data should be compatible with and able to feed into all widely used classification systems.

Rock mass classification is an integral part of the design process and will account for factors resulting from the interaction between the rock mass and the engineering structure to be designed. As such, a given volume of rock can have a wide range of classification value. It is a common pitfall to 'recycle' previous rock mass classification data obtained from a given project and apply it to new designs. This can lead to major errors in design. Another common practice that could lead to poor results is to perform rock mass classification 'generically', without a specific design task as a replacement to rock mass characterization.

Hadjigeorgiou and Harrison (2011) provide a good discussion on the different sources of uncertainty related to rock mass classification. They suggest that some of them are intrinsic to the method (like the inadequacies of RDQ estimation to quantify fracture intensity) and others (like the scale effect) are attributable to the many applications of classification systems outside of their original intent. Experience and training can be used to reduce the risk associated with these potential sources of inaccuracy.

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Appendix A

NGI rock mass classification system

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF}$$

Q = NGI rock quality index
RQD = Rock quality designation

Joint set number - *Jn*

Description	Value
Massive, no or few joints	.5 to 1.0
One joint set	2
One joint set and random	3
Two joint sets	4
Two joint sets and random	6
Three joint sets	9
Three joint sets and random	12
Four joint sets (sugar cubed)	15
Crushed rock, earth like	20

Joint roughness number - *Jr*

Description	Value
Discontinuous joints	4
Rough undulating	3
Smooth undulating	2
Slickensided, undulating	1.5
Rough planar	1.5
Smooth planar	1.0
Slickensided, planar	0.5
Thick infilling, no rock contact	1.0

Joint water assessment - *Jw*

Description	Value
Dry to minor inflow	1.0
Medium inflow or pressure to 250 KPa	0.66
Large inflow or pressure to 1MPa	0.5
Large inflow or pressure to 1 MPa outsawh of joint infiiling	0.33
Exceptionally high flow/pressure reduces with time	0.15
Exceptionally high flow/pressure no reduction with time	0.075

Stress assessment - *SRF*

Description	Value
Low confining stress (near surface) $\sigma_{UCS}/\sigma_1 > 200$	2.5
Medium confining stress $10 < \sigma_{UCS}/\sigma_1 < 200$	1.0
High stress $5 < \sigma_{UCS}/\sigma_1 < 10$	0.5–2.0
Mild rockburst $2.5\ \sigma_{ccc} < \sigma_{UCS}/\sigma_1 < 5$	5.0–10.0
Heavy rockburst $< \sigma_{UCS}/\sigma_1 < 2.5$	10–20
Weakness zones	
Single shear zones in competent rock	2.5
Multiple shear zones	10.0

Joint alteration number - *Ja*

Description	Value
Tightly healed	.75
Surface staining only	1.0
Slightly altered joint walls, clay free sandy particles	2.0
Silty and sandy clay coatings, small clay fraction (non softening)	3.0
Low friction, thin coating: chlorite, talc, clay etc.	4.0
Thin swelling clay	10.0
Thick swelling clay	2.0