Guidelines to minimize the occurrence of mega-wedge falls in rock caverns

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Abstract. Over the last decade, large rock caverns have been developed for storing vast volumes of hydrocarbons and in particular crude oil. In this context, large rock caverns have light support made of grouted steel or fibreglass rock bolts. Reinforcing cables are strictly prohibited to avoid leak paths for the product. Therefore, the risk of mega-wedge occurrence is high since the size of the potential mega-wedges is proportional to the cavern size. Some geometrical situations are more detrimental than others and the possibility of a local or extensive collapse be very high, including in rock masses which can be ranked as good and above. Such an apparent paradox could have been detrimental to the concept of large caverns because mega-wedges are extremely difficult to stabilize once discovered because rock bolts are generally too short to stabilize them. Anticipation is therefore the key. First, we clarify the term mega-wedge and then, analyse the various possibilities of occurrence in large caverns, as well as classical tunnels. Guidelines are proposed to identify whether the conditions are met for experiencing mega-wedge failure at hand. Two main geological structures, shear fractures and smooth-persistent-planar-spaced (SPPS) joints, are favourable for mega-wedge formation. These two fracture types are analysed and criteria are given to ensure a quick and efficient determination procedure. The field approach is synthesised by a decision chart, to be used at site, during the excavation works.

1. Introduction
Large caverns do exist for several decades, essentially in dam engineering for placing generators. Large underground caverns are also required for storing hydrocarbons. They look very similar in shape but their design is very different [1, 2, 3]. The most important difference is the way to achieve a stable excavation: hydropower caverns can benefit, if required by the rock mass conditions, of heavy support and reinforcement, using cable bolt and concrete lining for example, which is not the case for hydrocarbon rock caverns that remain unlined. This design is imposed by the hydrodynamic containment principle and the avoidance of gas migration along the cables which represents a potential risk for the tightness of these caverns [1]. Thus, hydrocarbon caverns use only rather small rock bolts (4 to 6 metres typically) which, in addition, are fully cemented, avoiding any gas migration.

Such a specific design for hydrocarbon storage caverns imposes two technical aspects that are not often grasped, i) unlined rock caverns for hydrocarbons are limited in size because of the support limitation and the maximum height reaches 30 to 32 metres and ii) hydrocarbon caverns are preferably
sited in good rock conditions. As an example, in the Q-system [4], the rock mass in which a hard rock cavern is excavated generally has a global Q-value equal to or higher than 10, limiting the support and reinforcement needs.

The recent increase of crude oil strategic stockpiling in many countries (China, India, etc.) induces the development of large rock caverns along with the increase of potential occurrence of mega-wedges. Basically, the size of wedges is related to the size of the caverns but in case of collapse, mega-wedges have a much higher impact in terms of damage with an increase of the construction schedule and the cost for the remedial actions. It is clear that if mega-wedge collapse occurs too often, it may become very difficult to convince decision makers about the interest of unlined caverns for storing hydrocarbons. Sound engineering and construction practice to avoid such situation must therefore be thought early in the projects.

An interesting predictive approach using structural geology has already been set to anticipate the location of mega-wedges in caverns during excavation before they are discovered [5, 6, 7]. A predictive approach is necessary because when a mega-wedge is discovered during the cavern excavation, it is generally already too late to support it and avoid the total collapse (figure 1). Based on the predictive structural approach that proved its worth, this paper analyses practical aspects that are sometimes difficult to perform for the site geologists and engineers in charge of the support, during construction:

- how to recognise the detrimental structures able to generate the mega-wedges?
- how to estimate site specific features such as the thickness of the detrimental fractures?
- is it possible to quantify the characteristics of detrimental fractures e.g., using C and Phi?

2. What is a mega-wedge?

The concept of mega-wedge is not new and this issue is directly linked to cavern excavation. The first publication mentioning the collapse of a “huge wedge block” was written in 2010 [8] for an accident that occurred in a butane cavern in South Korea in 1985 or 1986. The name mega-wedge was used by the first author of the present paper during a presentation made in 2012 for the Asian Rock Mechanics Symposium at Seoul on the subject of large wedge collapse [6]. The term mega-wedge is now widely used because relatively explicit whereas an absence of definition.

Indeed, a mega-wedge refers to a large or huge wedge; however, it seems useful to clarify the concept: A large wedge reaching the span of a tunnel could be named mega-wedge, but classically the profession refers to as an overbreak. Thus, we only use the term “mega-wedge” into caverns and, to distinguish it from overbreaks, limit it to the following specific situations:

- the full cavern section is excavated with several stages (top heading and benches for example)
- along a sidewall: the height of the wedge is equal to or higher than 80% of the maximum cavern height (around 24 metres in a 30m-high cavern) AND the length of the wedge is equal to or higher than the height of the cavern; the specificity of the mega-wedge is to occur during the excavation of the last benching phase (figure 1), giving almost impossible its stabilization with only the designed pattern rock bolts; if occurring during the excavation of the top heading or first bench, one can therefore speak of overbreak (in figure 4, sections A-A’ & B-B’ present overbreaks while only section C-C’ refers to a mega-wedge).
- along a roof: the length of the wedge exceeds the span of the cavern

As already mentioned by Vaskou and Gatelier [5] as the “paradox of very good rock”, mega-wedges do take place in good rock masses. In these good conditions, the mining teams, the geologists, etc. feel confident and do not work on failure modes as they do in fractured rock masses. However, on top of this subjective feeling of confidence, the real technical point is that the low frequency of structural defects induces the conditions for mega-wedge occurrence. Risk of experiencing failure of mega-wedges in heavily fractured masses is lower since support and reinforcement are installed at the face and adapted to stabilize the key block preventing major collapse.
Figure 1. Typical sequencing of excavation with mega-wedge occurring during benching from Vaskou & Gatelier [5].

Figure 2 presents three theoretical cases for mega-wedge formation [7], depending on the number of fractures at the periphery of the wedge: i) the standard situation (left) with one sub-vertical and one sub-horizontal fracture, ii) only one sub-vertical fracture (middle), the wedge detaching by traction under its own weight, iii) the theoretical case presented with an altered dyke wall. The latter has never been observed and probably cannot occur because most likely the collapse should start during heading, with a standard overbreak process, because of the jointing intensity. The latter case should however be considered with great attention if the support installed at the roof is not able to sustain the mega-wedge during benches excavation.

Figure 2. theoretical situation for mega-wedge formation (left: two main fractures; middle: only one main fracture; right: in fractured environment with a major defect) – only the left and middle case have already been observed by the authors.

3. Guidelines for the identification of mega-wedges
The predictive structural approach, already detailed in several publications [5, 6, 7] and named STAM (acronym for Special Technical Assessment Meeting), represents an efficient way that already proved its soundness. In this approach, all fractures are analysed as soon as possible on the site, say before the excavation. This is a step-by-step approach which is reproduced before heading, and then before each benching phase. We here do not detail this approach and the interested readers can refer to the above-mentioned references.

However, the difficulty is to practically determine whether a structure can act as a mega-wedge limit, sub-vertical potentially sliding fracture or sub-horizontal fracture. In the previous studies, this assessment has been made qualitatively, say only “important” structures being considered, such as small shear-crushed-zones. Indeed, to ease the site teams to make this selection, some quantification is required to avoid subjectivity and therefore possible risks.
This paper is the continuation of the geometrical and structural analysis initiated by Vaskou & Gatelier [7]. We have continued here the analysis in order to give practical elements to anticipate and learn how to discriminate specific structures that may act as sliding structures and create a mega-wedge. The authors know by experience how difficult a mega-wedge identification can be and the real need of a rather simple approach for on-site geologists and rock mechanical engineers.

In order to ensure easiness and efficiency, we have organised the selection and qualification of the mega-wedge forming structures in an identification chart (figure 4). The step-by-step procedure behind this identification chart goes from the general with the geometry to the particular with the characteristics of mega-wedge detrimental fractures (sub-vertical for the most frequent mega-wedge type, along sidewalls and sub-horizontal for mega-wedge along roofs, the latter being fewer).

3.1. Assessment of geometrical conditions

The initial condition for mega-wedge occurrence is the right geometry [5, 6]. Basically, along a sidewall, the sliding structure shall have an acute angle ranging from a few degrees (azimuth parallel to the cavern axis) to a maximum that cannot exceed 15 to locally 20 degrees. The dip angle of the concerned structure shall be very steep to allow the wedge to slide. A too steep dip angle (85° to 90°) minimises the apex and volume of the mega-wedge whereas a dip angle that is not steep enough (e.g. 60°) gives an enormous wedge volume but a very difficult sliding potentiality.

In granitic or gneissic hard rock environments, the authors have noticed that a fracture having a strike value of 15° to the cavern axis and a dip angle of 75° to the horizontal represents the worst case regarding the wedge volume and the potentiality of accident.

During the excavation, in the normal course of events, the team in charge of the mapping and stability issues considers geometry as the first step to select the number of fractures which could act as mega-wedge limiting fractures.

3.2. Potentially detrimental fractures that may limit mega-wedges

Even with the right geometry with respect to the cavern axis, all fractures cannot induce mega-wedges and specific characteristics are required to do so: a low shear strength and a persistent planar surface.

The structural knowledge of a site is the best tool to analyse the fractures and select the ones having the required characteristics. This analysis uses all the available geological information of the site, covering surface mapping, underground mapping performed during the excavation (face or developed maps), investigation boreholes and probes holes, cored or logged with BHTV-type wall imagery.

However, two very different candidates can exhibit low shear strength and planar surface: i) shear fractures, thick enough and filled either with crushed rock or gouge and ii) smooth and planar fractures, belonging to a joint set, filled or coated with material/mineral having a very low friction angle, contributing to easy sliding. These two different types of fracture are detailed below.

3.2.1. Shear fractures. Shear fractures (Mode 2 & 3 fractures; faults for geologists) are the perfect fracture types for mega-wedges because of a low residual friction angle due to the presence of sheared and smooth material inside the fault core [9]: either cataclastite, with granular breccia and gouge, say with some remaining pieces of intact rock or mylonite, very fine-grained with clayey mineral surrounded by intact ones [10]. To allow a mega-wedge to collapse, the limiting shear fracture shall have enough core thickness and 10 centimetres seems to be the threshold value for the structure to be continuous, persistent and planar. Statistical relations between displacement (slip) and length or displacement and magnitude do exist but there is almost no direct relationship in the literature between fault thickness and fault length. Using power-law relations, a 10-cm shear can be correlated with an average 1-m displacement value [11, 12] and the latter can be (poorly) correlated with a length of one to several hundred metres [13]. Indeed, the relations given by the authors [10, 11, 12, 13] only represent rough estimates however, in the case of a practical use, it is quite enough to know that a 10-cm thickness shear fracture has a length (persistence) that greatly exceeds the cavern dimensions. Thus, as soon as 10-cm thick shear fracture is detected, the assessment of its length becomes useless and the fracture shall be
considered as detrimental regarding mega-wedge stability. Such 10-cm value for the thickness fits well with real cases of mega-wedge in crude oil caverns but nevertheless will have to be confirmed in the future. It has been determined for granite and gneiss rock types and can be slightly different in sedimentary rocks. A ≥10-cm thick shear fracture is considered having a zero cohesion and a low friction angle; however, the authors recommend to assess the actual values of C and Phi by laboratory tests from cores or better with in situ testing.

3.2.2. Smooth and planar joints. A joint limiting a mega-wedge shall be smooth, persistent, planar and spaced (SPPS joint). These characteristics are detailed below:

- **Smooth**: by smooth we consider a joint filled or coated by soft minerals such as chlorite, graphite or serpentine, etc. corresponding to a Joint Alteration Number parameter (Ja) of 4 in the Q system [4]. Even in very hard rock environments such as granite and gneiss, this kind of joint is rare but may occurs locally. Roughness at large scale (waviness) is impossible to assess from cores or BHTV logs and structural correlations have to established between similar joints, during cavern excavation. Non continuous coating as well as filling by non-softening material shall systematically be rejected when assessing smooth joints.

- **Persistent**: a joint is much thinner than a shear fracture and then, its size (persistence or extension) shall be verified: if the joint is too small, it will not have the adequate geometry to form a 20-m to 30-m high mega-wedge. The assessment of this parameter is not trivial and, as compared to site investigation phase, it can be done with better accuracy during the course of excavation, when 2D and 3D information is made available. It implies not to perform the mapping face after face but to anticipate stability issues including top heading and benches, on several runs. Practically, when using the RMR [14] for characterizing the rock mass, the SPPS joint shall have a ranking of 6 for the parameter “Discontinuity length”.

- **Planar**: joints have to be planar enough to be able to slide with low stabilizing effect brought by the dilation angle (joint shear strength is mainly governed by the residual friction angle). If the Q-system is used, a SPPS joint shall typically have a “Joint Roughness Number” of 1.0 (smooth, planar) or even 0.5 in the case of slickensided joint [4].

- **Spaced**: the smooth joint shall be isolated or belonging to a set having a very wide spacing, wider than the cavern size; otherwise, only “small” wedges are likely to be observed and it is expected that the key block concept will prevent major collapse. The spacing required to provide a mega-wedge as seen on figure 2 (left and centre) is half of the cavern width or more (which typically gives around 10 metres in strategic crude oil caverns). In the RMR [14] approach, a SPPS joint has a rating of 20 in the parameter “Spacing of Discontinuities”.

3.3. Three-dimensional structural analysis

For the formation of mega-wedges, shear fractures are more frequent than SPPS joints. This is simply due to the fact that even if smooth joints are frequent, SPPS joints (smooth and planar, over 20 to 30-m long persistent, widely spaced joints) are rather uncommon.

Whatever the type, SPPS joint or shear fracture, the characterization requires geological observations and when possible, cross-checking using core boreholes or BHTV logging. In hydrocarbon caverns, horizontal water curtain boreholes, located generally around 20 metres above the cavern crown, are used to start as early as possible the correlations (between boreholes and top heading). Additionally, during cavern excavation, small horizontal investigation holes drilled from the cavern wall can solve the issue [5].

Accurate structural observations carried out in 3D are required, in parallel with mechanical modelling, to assess various stability scenarios and anticipate the worst situation before reaching it in cavern. The mega-wedge limiting fractures are never strictly parallel to cavern axis and from that geometrical situation, they do cross the caverns at other locations where they only induce over-breaks (instead of mega-wedges). This is visualised on figure 3 with a detrimental structure reaching a cavern at the base of the top heading, of a first bench and finally of the last bench. Depending on the excavation
direction and the geometry of the structure, the mega-wedge limiting fracture may be observed, analysed and even tested before reaching the worst situation where a mega-wedge becomes unavoidable (section C-C’). Similarly, if parallel caverns are planned, the structural information gathered on the first one shall be used for the others, as far as the extension of the concerned smooth joints allow them to cross several caverns.

Figure 3. various effects of the same detrimental fracture crossing a cavern

Section A-A’: fracture in top heading
Section B-B’: fracture in first bench
Section C-C’: fracture in last bench

When using this approach, many potential structures are identified during the early steps of cavern excavation and then, with the increase of the structural knowledge, the number of fractures being potential candidates for a mega-wedge formation greatly reduce. Generally, when starting the excavation of top headings, potentially detrimental fractures may easily reach one or several dozen but when starting the first bench, the number becomes much lower. At this time, we highly recommend not to wait until the last bench is excavated to investigate these potential structures, by boreholes or adit [7] and keep the possibility to treat the potentially unstable zones either by heavy support or even local reduction of the cavern span.

4. Identification chart
In order to ease the mega-wedge identification for site geologists and rock mechanical engineers, a decision chart has been elaborated. This chart distinguishes the shear fractures from SPPS joints and summarises the various parameters that have to be considered.

The approach is a step-by-step one that works by elimination: as soon as a potential structure deviates from the characteristics presented in the chart, the fracture is eliminated and the potential mega-wedge as well. This fracture will indeed be able to induce overbreaks (and will have to be treated so) but not mega-wedges.
5. Discussion

One potential objective of the authors was to provide a field description of the mega-wedge limiting fractures as well as a certain quantification of their characteristics. Both potential shear fractures and smooth and planar joints are described and an identification chart (figure 4) is provided to simply but efficiently help site geologists and rock mechanical engineers. In this sense, the first objective is reached.

Regarding the second objective, quantification is only given for the thickness of the shear fractures but not for the cohesion and the friction angle. The authors consider that, scientifically speaking, they do not have enough data in order to conduct an empirical approach (this is also due to the fact that when a mega-wedge collapse occurs in an industrial project, there is no (or too few) communications on the accident). Thus, providing values for C and Phi would lead to a wide range (at least for Phi) and would not help site teams. In addition, C and Phi can rather easily be tested in laboratory on SPPS joint samples but testing shear fractures is more difficult (geomechanical in-situ tests have almost disappeared for a few decades except in research projects).

Although not discussed in the paper, once the potentiality of mega-wedges confirmed, a mechanical stability analysis must be implemented to define which remedial action shall be put in place considering the temporary critical phase where support is not yet installed in the newly excavated part of the cavern. Due to the geometrical nature of the problem, 3D mechanical analysis is recommended including excavation induced in-situ stresses and hydrostatic pressure in presence of water bearing geological structures. Neglecting in-situ stresses might lead to overconservative results whereas neglecting hydrostatic pressure might lead to optimistic ones.
A risk management can efficiently achieve the objective by i) reviewing the geological conditions gathered during the excavation of the top heading ii) evaluating and localizing the areas with risk of mega-wedge, iii) checking that the support pattern is enough to sustain the potential mega-wedge, considering also temporary situation when only partial support is installed and iv) defining and implementing on site the required specific support for the considered mega-wedges.

6. Conclusions
Two main structural defects are identified as potential mega-wedge limiting fractures: the shear fractures are the most common ones, and the smooth-persistent-planar-spaced (SPPS) joints. Both are analysed and various criteria are given to practically distinguish them. In addition, a decision chart is elaborated to allow the personnel at site to assess the detrimental fractures quickly and efficiently. The approach, used by the authors, has already proved its efficiency, but the number of cases (occurrence of mega-wedges and collapse as well) is too few and needs to be validated by more cases in various geological environments.

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