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# Simulation of Tectonic Deformation and Large-Area Casing Shear Mechanisms----Part B: Geomechanics[1]

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**ABSTRACT:** We present a study on the causes of large-area casing deformation mechanisms in one area experiencing extensive casing shear in the Daqing Oilfield, China. We use stress data and numerical stress simulation experiments under various injection situations. Instead of qualitatively stating the cause of large areas of casing shear, as in most previous work, we carried out a series of analysis of the effect of rock properties, casing displacement experiments under *in situ* stress changes, and slip mechanism determination. We developed a mathematical model to quantitatively compute the coupled effect between the tectonic stress field and the induced stresses from high-pressure water injection. Our study indicates that large-area casing shear in Daqing Oilfield occurs in weak lithological interfaces within the overburden; the increase of water content in shale formations decreases cohesion and the friction angle (shear resistance degradation); and, variation of injection pressure generates a clear perturbation of the regional stress field. Once the maximum compressive stress parallels or nearly parallels the maximum differential pressure gradient, the stability of strata in shear is severely compromised. Simulation results for various schemes show that so long as the injection pressure and pressure differential between blocks are controlled to be less than 12.7 MPa and 0.86 MPa respectively, formation shear slip along horizontal surfaces will no longer occur. Multi-disciplinary casing shear mitigation methods are recommended. Our method and the results can serve as a reference for other similar oilfield circumstances.

## 1. INTRODUCTION

Casing shear has long been a geological engineering issue in the development of Daqing Oilfield, China. The number of wells evidencing casing shear increases each year. Although various measures have been tried, the situation did not improve greatly over the previous decade. By the end of 2004, the cumulative number of wells showing casing shear reached 18.77% of total wells, and the annual economical loss from casing shear is more than $125million [1]. Furthermore, in some reservoirs, casing shear occurred extensively in large areas.

Causes of casing shear in large area were varied. After years of research work and field investigations, it was concluded that there were two main reasons. One reason appeared to be that injected water invades into mudstones and shale and decreases the shear strength and friction coefficient; as a result, creep deformation will take place under ambient differential stresses. The second reason was that unbalanced water injection causes significant reservoir pressure differences, which are of course accompanied by strains [1]. When the pressure differences were large enough, casing shear would occur through the accumulation of deformation along an interface. Unfortunately, these studies initially were based on qualitative interpretation, and no quantitative analyses for the causes have been reported.

For many years, attempts have been made to mitigate the casing shear problem; various repair and work-over technologies have been developed [1,2], such as hydraulic cement squeezing and

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[1] Part A is referenced as Han et al. 2006.

expanding sealing cementing methods, explosive welding and sealing cementing technology, and long-interval sealing and cementing technology. However, these are mainly work-over or repair techniques for single wells intended to also effect pressure control measures for wells in sand bodies. Nothing has been reported quantitatively about the extent of water invasion and the possibility of establishing pressure difference limits over a large region. Although repair techniques are successful for single wells, the total percentage of casing loss is still very high (see figure 1).

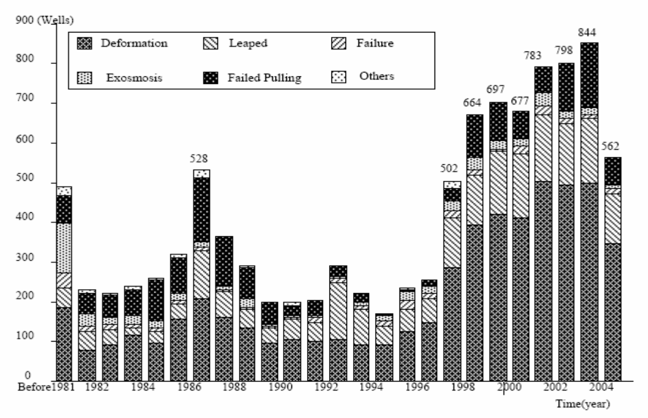

Figure 1. Casing Shear Occurrences in Daqing Oilfield from 1981 to 2004 (peak of 844 shear events in 2003, he et al. 2005 [5])

In this paper, we examine the rock properties of the area, analyze the slip mechanisms in the context of the in-situ stress, and developed a series of mathematical models to quantitatively compute the coupled effect between the tectonic stress field and the induced stresses from high-pressure water injection. Based on experimental field studies of the influence of injection pressure on the injection-induced strain and displacement fields, the regional casing deformation phenomenon was simulated numerically, the technical limits of casing deformation occurrence were demarcated, and casing deformation prevention methods were suggested.

This paper will emphasis the geomechanics; Part A [5] of the article has details about operational factors.

## 2. ROCK PROPERTIES

Daqing Oilfield reservoirs are encountered at depths from 700 to 1200 m. Many different oil-bearing zones exist, and there is a high degree of heterogeneity. Oil zones are parts of a Lower Cretaceous, fluvio-deltaic sedimentary sequence that contains up to 100 individual sand layers with thickness ranging from 0.2 meters to 20 meters [3]. These layers are mainly sandstone or siltstone with a porosity range from 20% to 30% (average 25%) and a permeability range from 20 to 1600 mD (average 230 mD). Furthermore, there are a number of stacked sand-slit-shale sequences, and a thick overburden shale (~60 m).

Figure 2 gives a general description of the sand-silt-shale sequences with the thick shale layer in the upper overburden rocks. Core observation indicated that the shale layer is very fissile and weak, and probably has a significantly lower *in situ* stiffness, compared to the arenites. Statistical data indicate that the majority of casing shear events did not occur in the pay zone intervals; nearly 70% of casing shear occurred at the bottom of this thick upper shale layer and were mainly concentrated in seven areas, among which the northern Xing1-3B block was the largest (5.7 km$^2$) [1].

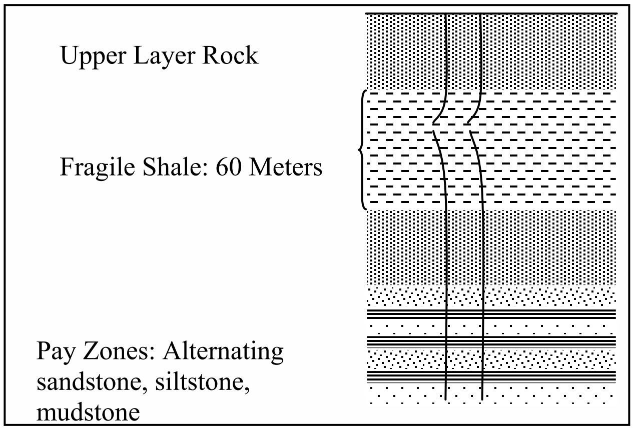

Figure 2. Sketch of Reservoir Sequence.

## 3. CASING DISPLACEMENT UNDER IN-SITU STRESS CHANGE

To analyze stress/strain behavior and rock strength, we normally identify and estimate the three principal stresses: the major - $\sigma_1$ - intermediate -$\sigma_2$ - and minor - $\sigma_3$. It is assumed that the vertical stress - $\sigma_v$ - is one of the principal stresses; therefore, the other two are the maximum and minimum horizontal stresses, $\sigma_H$ and $\sigma_h$, respectively [4].

The *in situ* stress field is not constant: it is subject to change under various conditions such as differential depletion and injection pressure changes. Taking the northern Xing1-3B area as an example, the direction of the original $\sigma_H$ in the area is N80°E. The variation of local *in situ* stress direction and its influence on casing displacement were observed under changing injection situations [5]. According to the field data, the measured direction change of casing displacement of individual well locations was up to 65° under a pressure change of about 4 MPa. The observed casing displacement range was in the range 0.05 ~ 0.08 mm (well below distress levels, as measurements were taken over only a short interval).

The above observations indicated that the variation of injection pressure generates a perturbation on the regional stress field. The result also showed that the impact of injection well rows and their geometrical arrangement on the regional stress field could not be neglected.

## 4. SLIP MECHANISM

Casing deformation is a geological engineering issue with complex mechanisms and multiple causal factors that include drilling and well completions, lithostratigraphy, and injection and production strategies. There are generally three typical forms that casing shear in Daqing takes [4]:

a. Localized horizontal shear at weak lithological interfaces within the overburden during reservoir compaction or heave.
b. Localized horizontal shear at the top of a specific production or injection interval caused by volume changes in the interval that arise from pressure and temperature changes.
c. Casing buckling and shear within the producing interval, primarily along perforations, and mainly because of axial buckling when lateral constraint is removed, but occasionally due to shearing at an intraformational lithological interface.

It was also observed that the overburden failures are in general associated with large-scale formation movements [6]. According to rock properties analyses and statistical casing damage assessment, casing shear in large areas within Daqing Oilfield occurs on weak lithological interfaces within the overburden. The variations in the stress fields and the induced strain caused by changes in the injection/production factors are the key reasons.

### *4.1 Formation Shear*

As stated, reservoirs in Daqing oilfields are not homogeneous. This inhomogeneity in strength and stiffness resulted in the formation of a shear band along a lithological interface (high stiffness contrast, therefore a high shear stress contrast) with the weak shale (low strength). In general, rather than general shear straining, one would expect shear distortion in such media to coalesce on a single interface, an observation confirmed in fields in Alberta, California, the North Sea and elsewhere [6]. In Daqing, the thick weak overburden shale is less stiff than the underlying siltstone or sandstone, creating the requisite contrast that leads to a shear stress concentration on the interface. Hence, casing distortion is largely localized on the basal surface of the thick shale.

### *4.2 Slip Criterion*

The natural shear stresses, $\tau$, exert a pre-existing thrust to the rock mass along the failure plane; when the thrust exceeds the slip criterion, slip is evidenced, but as long as it does not, the casing remains largely undeformed. Whether the casing is in distress or not depends on the magnitude of the shear slip along the critical weak surface. Furthermore, if the shale is presheared by natural processes, evidenced as slickensides and bedding plane separation, the critical surface may be at a condition close to the minimum strength (called the residual strength in soil mechanics).

The maximum shear resistance of shale is assumed to follow the Mohr-Coulomb law (Figure 3):

$$\tau_{\max} = c' + \sigma'_n \tan\phi' \qquad （1）$$

where, $\tau_{\max}$ is the maximum rock shear resistance $(MPa)$； $c'$ is the cohesion $(MPa)$； $\phi'$ is the angle of friction (°), and $\sigma'_n$ is the normal stress $(MPa)$; and

$$\sigma'_n = \sigma_n - p_f \qquad (2)$$

where $p_f$ is pore pressure $(MPa)$.

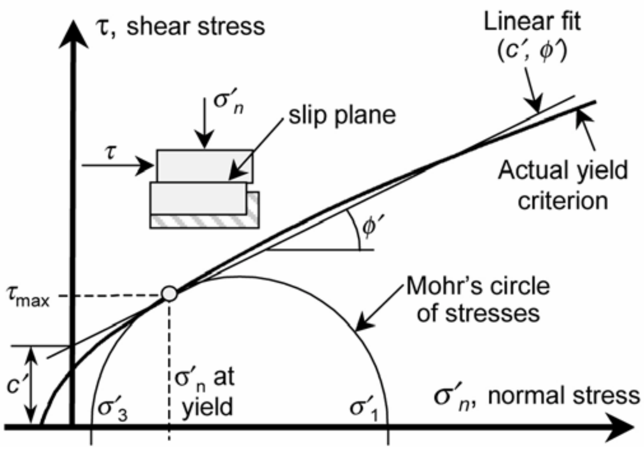

Figure 3. Mohr-Coulomb Criterion and Stress

Because the pore fluid pressure, $p_f$, also has an influence to the rock shear resistance, higher induced fluid pressures mean lower effective stresses. High-pressure injection causes normal stress decrease and in turn lowers the maximum shear resistance. In addition, because the shale is of low permeability, an elevated pore pressure will occur first along the interface with the more permeable sandstone or siltstone, adding another mechanism for localization of the shear deformation along the lithological interface.

### 4.3 Water Content Influence

As stated, water content in the shale formation has an influence on the rock shear resistance. In subsurface conditions, a high pore pressure and the presence of available water can soften the shale through swelling (water uptake). The higher pore fluid pressures means lower effective stresses ($\sigma'_n = \sigma_n - p_f$). Thus, prolonged high-pressure injection not only causes normal stress decrease and a lowered maximum shear resistance, an increase in the water content of the shale will lead to a diminution (degradation) of cohesion, perhaps even a reduced friction angle in the critical shale-sandstone interface where shear stresses tend to be concentrated. Triaxial testing of shale specimens from the critically sheared region of one of the wells in Daqing Oilfield verified an approximate relationship between the shale seam cohesion, friction angle, and water content ($f_w$)：

$$c' = 96 - 5 \times f_w \qquad （3）$$

$$\phi' = 34 - 2.7 \times f_w \qquad （4）$$

where $c'$ is the cohesion ($MPa$)； $f_w$ is water content (%); $\phi'$ is the angle of friction (°).

Under normal circumstance, the shale contains only 3 – 5% water, whereas, as the result of the prolonged of high pressure water injection, shale was observed to develop a higher water content. In one of the damaged wells, the shale water content was measured at ~10%. Supposing that this occurred from swelling, if the relationships stated above apply, using the MC criterion, the maximum shear resistance of the shale will decrease by $0.378 \cdot \sigma'_n$ MPa. Furthermore, the area affected by such a strength reduction will grow with time as the pore pressures diffuse into the shale at an increasingly regional scale. This weakening effect is "additive" to the pore pressure effect, and when a sufficiently large area has been affected, the shale strength is overcome, making it possible for shear displacement to take place over a large area, akin to a thrust fault plane. Given the difficulty in precise assessments of conditions and material properties in situ, it is hard to unequivocally prove that the weakening effect is substantial, but the gradual development of shear distortion along planes is considered to be partly the result of water weakening, and partly the result of scale. Only when the scale length of the affected area exceeds a critical size can sufficient shear stress be developed to cause shear plane development.

### 4.4 Coupling with Natural Stress Fields

Obviously, the sliding of rock is closely related to the shearing resistance and the thrust magnitude, both natural and induced. The highest thrust (i.e. the maximum shear stress), which is along planes 45° from the principal stress directions, is defined as $(\sigma'_1 + \sigma'_3)/2$. The larger the natural, pre-existing difference in the principal stresses, the greater the shear stress, and the closer the rock is to a state of failure or shear slip (refer to Figure 3).

The stress field is perturbed by the pore pressure changes induced by high-pressure injection activities. That is to say, there is a departure from the natural principal stress fields caused by the diffusion of higher pore pressures. This is the coupling effect with the natural stresses, and it is not sufficient to perform a pure pore pressure analysis and simply take the calculated pore pressures and introduce them into a criterion based on the natural stress fields. The small volume chances arising because of the natural compressibility of the rocks lead to an internal reaction in the rock mass, causing the local principal stresses to change in a complex manner, given the natural heterogeneity.

In order to understand the disturbance caused by injection pressures on the original terrestrial stresses, field studies comprising stress measurements under various water injection conditions were carried out [5]. According to the results of the analysis, both stress directions and magnitudes are locally changed.

The fluid pressure levels between blocks are different because of the areal horizontal heterogeneity. In other words, there are pressure differences among the blocks, and these pressure differences are not necessarily distributed in a uniform manner. The induced stress fields associated with each injection well overlap with each other. We note that once the maximum compressive stress parallels or nearly parallels the maximum differential pressure gradient, which is controlled by the geometry of the injection strategy, the coupling effect will give rise to a vectorial change in the shearing resistance that severely compromises the shearing resistance. The strata will then show slip in a direction corresponding to the vector that is co-axial with the maximum pressure gradient. This resembles a distributed but spatially oriented body force, vectorial but distributed in nature, instead of being a point force.

## 5. NUMERICAL SIMULATION

In 1990, Osmar A. *et al* [3] analyzed the reservoir behavior and production trends in Daqing Oilfield by using geological models and simulation methods but unfortunately, the casing shear issue was not a major concern in their research. In order to quantitatively analyze large-area casing shear, and to verify the previous stress analysis, a numerical simulation model was constructed and executed parametrically. The simulation was based on rock property analysis in the field and in the laboratory, and on the *in situ* stress information, giving a calibration possibility. Of course, the rock mechanics model following the basic principles of stress equilibrium, and particular care was placed on the nature of the rheological equations used to describe the rock mass, given the data that existed on the *in situ* state and alterations thereto. The area to be simulated was selected to be the largest large-area casing shear region in the oilfield, the northern Xing1-3B block [5].

Both the simulated casing displacement direction and the displacement distance agreed with the actual measured data. The numerical simulation carried out in the area indicated that the arrangement of injector lines and the variation of injection pressure induce a substantial vectorial perturbation on the local stress field. Furthermore, simulation results also showed that so long as the injection pressure and pressure differential between blocks are controlled to be less than 12.7 MPa and 0.86 MPa respectively, formation shear slip along a horizontal surface would no longer occur [5]. These figures were arrived at with a field-calibrated approach, therefore, they seem relatively reliable.

## 6. RECOMMENDED CURES

Strengthening of casings can achieve 20% or more improvement in casing collapse resistance and this has been proven in laboratory tests [7]. Therefore, carefully cemented casing has been widely viewed as a means to strengthen casing and prevent casing shears. This was also considered and implemented in the Daqing Oilfield. However, when the size of the induced shear planes is so large, the presence of a “strong” casing cannot resist slip, it may at best only retard the process to some extent. The stiffer the casing-cement system, the more likely it is to focus (attract) stresses [4]. Furthermore, the existence of cementing voids, especially longitudinal voids in the cement sheath, can lead to point loads on the casing, reducing the failure stress by at least 50% [7]. Considering the fact that in Daqing Oilfield the number of sheared wells kept increasing in spite of various efforts to improve cementing quality, some alternative means of mitigation such as allowing more compliance between casing and formation, or reducing the magnitude of slip along planes by altering the injection geometry, could be tried.

### *6.1 Compliance between Casing and Formation*

In typical large-area casing shear cases, stiff casings may attract stress. By increasing compliance between the casing system and the formation, the casing can deform over a greater length and shear stress can be released somewhat before casing shear takes place. Figure 4 illustrates the details of an operation for such a compliant completion.

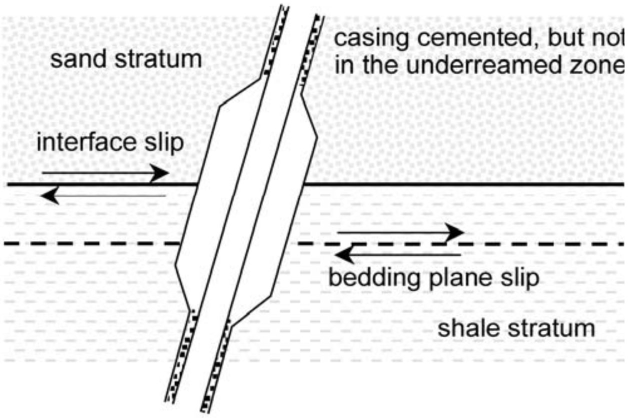

Figure 4. Illustration of Compliance between Casing and Slip Plane. The susceptible interface is underreamed and remains uncemented

In Figure 4, the most susceptible slip zone is underreamed, the hole is enlarged compared to other parts of the bore hole, and no stiff cement is added, to avoid "attracting" stress. Displacements can occur in the larger space without casing shear.

### *6.2 Avoiding Slip Planes*

One may avoid a casing stress concentration with horizontal or directional wells to bypass the likely slip area by placing wellbores in regions where the shear magnitude is lower than adjacent areas. Such an idea is illustrated in Figure 5. The concept is to identify where the shear stress and the slip zone are most serious. In a reservoir with a given production strategy and stratigraphy, numerical geomechanical modeling can be used to indicate where the shear stresses and slip are likely to be the greatest.

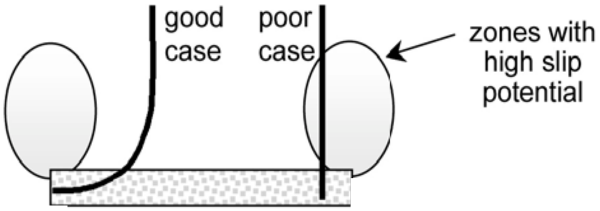

Figure 5. Illustration of Avoiding Slip Planes. Wellbores can be placed in regions having smaller shear slip.

For the specific case in Daqing Oilfield, it is easier to carry out such an approach because the most serious areas have been determined.

### *6.3 Reservoir Stress Management*

Reservoir stress management approaches can be used to monitor the stress status, balance the reservoir pressure system, and minimize pressure differences between blocks. This should mitigate in part the problem of large areas of casing shear

In reservoir stress management, the first task is to monitor the effects. Deformation measurements can be based on tilt-meters (very small induced surface strains) in shallow or deeper wells to deconvolve the displacement field. This was done in the investigation operations in the northern Xing1-3B block area [5]. Using micro-seismic monitoring [4] is also a possible means of identifying the susceptible slip zones, although once emissions are sufficiently detectable, slip may already be sufficient to have led to casing distress.

Then, 3D coupled geomechanical models used in conjunction with reservoir pressure evolution models and parametric numerical simulation can give predictions of the shear stresses induced by a process. The prediction must be confirmed and calibrated with real data.

### *6.4 Multi-disciplinary Method*

For reservoirs with large-scale heterogeneities and with problems of serious large-area casing shear issues like those in Daqing Oilfield, it is more pragmatic to adopt many curative methods at the same time than to rely on one single method. Also, it is more realistic to apply the tactics simultaneously to reduce casing shear incidence and rate, rather than seeking to eliminate it entirely [4]. Under these oilfield extractive strategies, shearing will inevitably occur; all that we can do is to reduce its magnitude and impact on oil production.

## 7. CONCLUSIONS

Rock properties analysis is the only possible basis for large-area casing shear issues study. Large-area casing shear in Daqing Oilfield occurred in weak lithological interfaces within the overburden. The existence of a thick fragile shale formation and the high vertical heterogeneity are the intrinsic causes of large area casing failure. The horizontal heterogeneity causes unbalanced pressure difference between blocks. The long period of high-pressure injection is the external stimulation leading to the large area formation slip.

Variation of injection pressure has obvious disturbance to the regional stress field. A pressure change of about 4 MPa can change the direction of casing displacement up to 65°, and can cause casing displacement magnitude change of 0.05 to 0.08 mm.

Water content in the shale formation has an influence on rock shear resistance. In subsurface conditions, higher water contents are correlated with higher pore pressures. Higher pressures mean lower effective stresses ($\sigma'_n = \sigma_n - p_f$). Therefore high-pressure injection causes normal stress decrease and in turn lowers the maximum shear resistance. Also, higher water content in shale decreases cohesion and friction angle of the shale formation. In the studied area, a 5% increase of water content in shale can decrease the maximum shear resistance of shale approximately 40% of the normal stress.

The results also showed that the impact of injection well rows and geometrical arrangement on the regional stress field cannot be neglected. Once the arrangement of injection well rows is chosen and injection pressures change, the resultant additional stress fields will overlap additively. When the overlapped maximal principal stress parallels to or nearly parallels to the south-north direction pressure differential, the stability of the strata will be seriously impaired. Especially, regularly distributed injection and production well rows are the most severe factors driving strata creep and slide. The change in this creep and slip displacement field is the fundamental reason for the serious casing deformation damage in Daqing Oilfield.

Variation of injection pressure can induce a substantial perturbation on the local stress field. Once the maximum compressive stress parallels or nearly parallels the differential pressure, the stability of strata in shear is severely compromised, and when the thrust stress imposed exceeds the shearing resistance, the strata will slip in a direction corresponding to the vector from high pressure to low-pressure areas. In the studied area, so long as the injection pressure and pressure differential between blocks are controlled to be less than 12.7 MPa and 0.86 MPa respectively, formation shear slip along a horizontal surface will no longer occur. Some alternative multi-disciplinary means of mitigation, such as allowing more compliance between casing and formation, or reducing the magnitude of slip along planes, together with reservoir stress management and high quality well installation, should be tried.

## ACKNOWLEDGEMENT

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## NOMENCLATURE

*$c'$ = cohesion of the rock*
$f_w$ = *water content*
$p_f$ = *pore pressure*
$\phi'$ = *friction angle*
$\sigma_n$ = *normal stress*
$\sigma_1$ = *major principal stress*
$\sigma_2$ = *intermediate principal stress*
$\sigma_3$ = *minor principal stress*
$\sigma_{\mathrm{v}}$ = *vertical stress*
$\sigma_{\mathrm{H}}$ = *maximum horizontal stress*
$\sigma_{\mathrm{h}}$ = *minimum horizontal stress*
$\sigma'_n$ = *effective stress normal to a slip plane*
$\sigma'_1$ = *effective major principal stress*
$\sigma'_2$ = *effective intermediate principal stress*
$\sigma'_3$ = *effective minor principal stress*
$\sigma'_{\mathrm{v}}$ = *effective vertical stress*
$\sigma'_{\mathrm{H}}$ = *effective maximum horizontal stress*
$\sigma'_{\mathrm{h}}$ = *effective minimum horizontal stress*
$\tau$ = *natural shear stress*
$\tau_{\max}$ = *maximum shear stress in the Mohr-Coulomb slip criterion*

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