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STRESSES IN THE IMMEDIATE STONE ROOF OF A COAL MINE ROADWAY

Ross Seedsman[1]

ABSTRACT: An analytical approach to designing roof support needs a model that quantifies the magnitude of the stresses acting in the immediate roof. There is a large amount of measurement data on stresses above pillars but few models for the stresses within the bolting horizon. Very small roof deflections result in substantial relaxation of horizontal stresses in the immediate roof. Increased vertical and horizontal stresses at the maingate increase the height of compressive failure and hence the "softened zone" and this leads to greater loading on the bolted roof beam. The situation does not change in a material way at the tailgate unless there is major yielding of the side of the roadway in which case the horizontal stresses in the roof line may become tensile.

INTRODUCTION

ACARP project C14029 documents a series of analytical tools to assist in specifying roof and rib support. These tools are applied in a logical framework in which there are tests for compressive and tensile failure and tests for movement along discontinuities. Models for the stresses applied to the bolted horizon were required. There can be no doubting that considerations of the stress redistribution are complex, involving interactions between the in-situ stresses and the large longwall goaf, stress redistribution around the roadway itself, and any body stresses induced by the deformation and movement of the immediate rock and coal mass. This paper provides a summary of the model development for stone roof.

IN-SITU STRESSES

It is not possible to predict the state of stress in the ground from simply a knowledge of the depth of cover. The approach should be to apply regional knowledge of the general stress field to any point measurements at the mine site, and particularly to observations of how excavations behave underground. In the latter case, it is essential not to jump to the paradigm that all roof falls are due to elevated horizontal stresses; this is unlikely to be the case and certainly not once the roof is supported at the densities typical of current Australian coal operations.

Data from New South Wales and Queensland (Nemcik et al, 2006) show that the ratio of the horizontal stress to the vertical stress in stone is typically between 1.0 and 2.5 times at typical mining depths, with even higher ratio values at shallow depths. It is noted that there is a significantly different stress field in coal.

Stress magnitudes should be lower in faulted ground. Elevated deviatoric stresses generate failure and on a large scale this is evidenced as faults, more often than not with associated sub-parallel joints. Once the rock is broken, the maximum deviatoric stresses within the broken rock are lower and are controlled predominantly by the frictional resistance of the surfaces generated by the faulting. The poor roof conditions that are typically encountered in the vicinity of thrust faults are not the result of elevated horizontal stresses but are a consequence of the presence of broken rock.

REDISTIBUTION ABOUT A LONGWALL

Our knowledge of stresses and stress changes is based on measurements in stone above the chain pillars and about 5m - 10m into the roof. These are not the stresses at the roof line.

Using standard chain pillar design methods (Colwell, 1998), the vertical stress is doubled at the maingate corner. There is a concentration of horizontal stresses above the chain pillar at the maingate corner and a reduction in the horizontal stresses behind the face adjacent to the goaf

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(Figure 1). The magnitude of the concentration of the major principal horizontal stress depends on the angle between the stress axis and gateroad direction, with the possibility that there is a doubling of the magnitude at a 45^{o} angle.

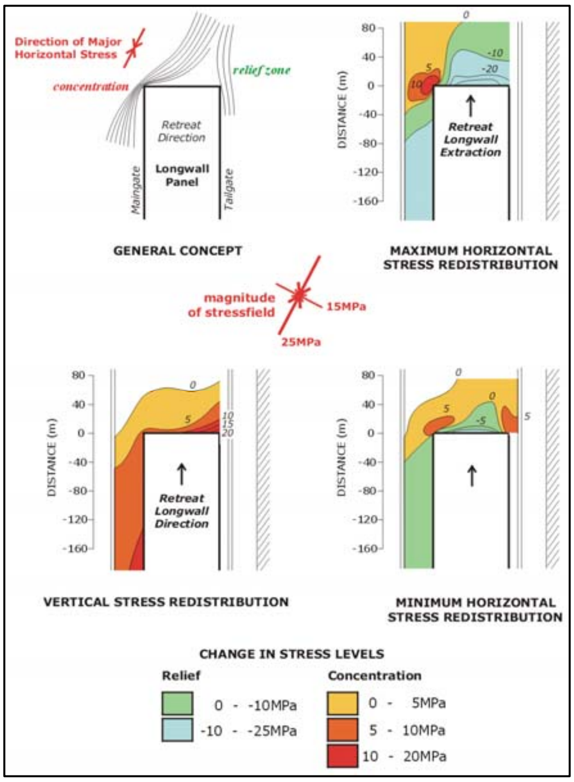


Figure 1 - General pattern of vertical and horizontal stress redistribution (Gale 2008)

There is also an increase in the vertical stress observed above the pillar behind the face and a large reduction in the horizontal stress. Tarrant (2006) provides the mechanism for this large stress relief – shear along bedding in the direction of the goaf.

Shen et al (2006) instrumented a tailgate at Ulan at a depth of about 200m and showed that overall the vertical stress increased by 3-4 MPa while at the same time the horizontal stress decreased by up to about 1 MPa. The overall pattern in the tailgate is consistent with increase in vertical stresses implicit in the pillar design models and a further reduction in horizontal stresses resulting from more lateral translation of the roof into the now two longwall voids.

The simultaneous increases in both the horizontal and vertical stress are significant in terms of the stresses induced in the immediate roof of an excavation. Depending on the concentration factor that applies to the horizontal stress, it is possible that the “vertical” stress acting in the maingate may become the largest stress component, and certainly the vertical stress is the largest stress component behind the face and in the tailgate. There is no published information on the rotation of the principal stress axes around a longwall. Making the simplifying assumption that the vertical stress is a principal stress, Figure 2 shows the way in which the K ratio (horizontal/vertical) can change.

ELASTIC STRESS REDISTRIBUTION AROUND A RECTANGULAR ROADWAY

The initial response of a roadway can be considered to be elastic and many of the failure modes that are seen develop in response to these elastic stress redistributions. It is important to realise that elastic analyses are only applicable for the initial formation of the roadway as it has been shown that even small deformations result in major relaxations in the roof and redistributions to elsewhere in the system (see later).

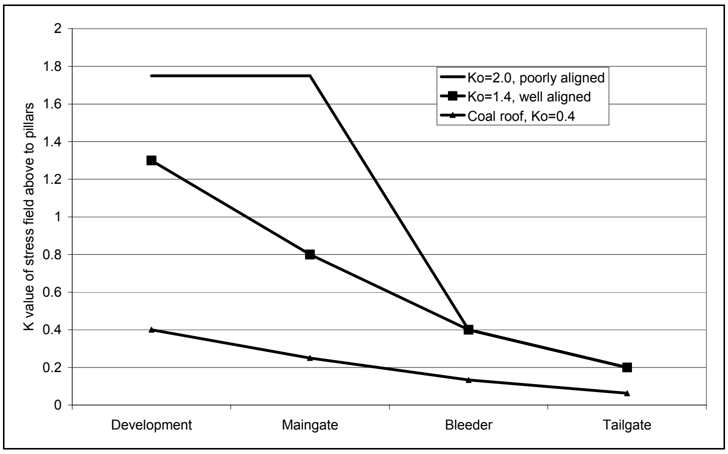


Figure 2 - Indicative changes in the K ratio

Figures 3 and 4 present the results of the analyses of a typical rectangular roadway (2.8m high and 5.2m wide) for two K ratio values - 2.0 and 0.2 with the major principal stress being 10 MPa. Two stress components are presented: deviatoric stress ($\sigma_1 - \sigma_3$) which is the driver for compressive/shear failure (Figure 3) and σ_h – the horizontal stress which, if tensile, would allow the onset of shear along vertical joints (Figure 4). A summary of the results for a range of other K values is presented in Table 1.

When the K value is greater than 1, the contours of deviatoric stress tend to form an arch over the roof line but this does not develop when the K values are less than 1 (Figure 3). The highest values are at the roof/rib corner with the magnitude ranging from about 30 MPa for a K value of 1.0 to about 21 MPa for higher or lower K values. It is this concentration at the roof corners that is one of the mechanisms for stress guttering.

Table 1- Summary of stresses for rectangular roadway (σ_1 = 10 MPa)

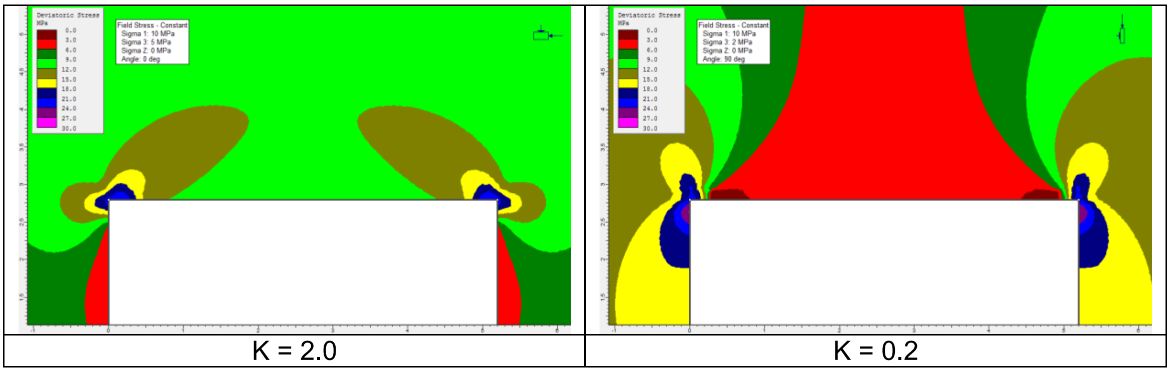
K	Horizontal stress at 0.2m into roof at centerline (MPa)	Horizontal stress 0.1m from rib and 0.1m into roof (MPa)	Maximum deviatoric stress 0.1m from rib and 0.1m into roof (MPa)
0.2	-5	8.3	19.5
0.5	-1	13.5	21
1.0	6	24	27
1.4	8	22	24
1.7	9	22	21
2.0	10	21	21

The centreline of the roof has tensile horizontal stress for K values less than 0.5, and the roof stress becomes increasingly compressive as the K value increases. Near the rib line the horizontal stresses are compressive for all K values (Figure 4).

NON LINEAR STRESS REDISTRIBUTIONS

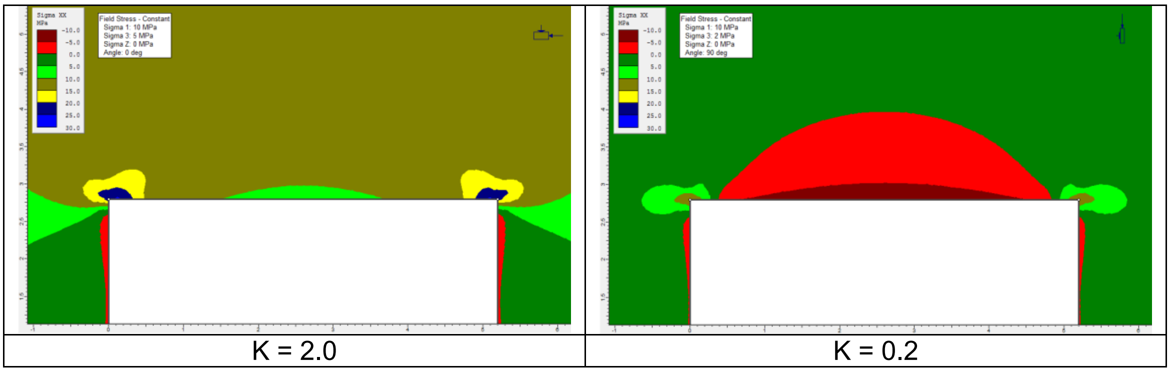
Non-linear (=not elastic) stress behaviour is a key feature of underground roadway behaviour. Unfortunately, with the current state of the art, it is difficult to incorporate this behaviour into numerical analyses, and certainly not in routine design. Fortunately, it would appear not to be necessary.

It is well established that coal mine roofs deform into the excavation as the roadway is advanced. This deformation zone is routinely identified with roof extensometry and is loosely referred as the "softened zone" or "the height of softening". Whilst the term is somewhat misleading, it does have the advantage of focusing attention on what the impact may be in terms of the immediate roof stresses. Softening implies a lower modulus of deformation, which should mean that there is less of an ability to bear stresses compared to stiffer units nearby.



K = 2.0 K = 0.2

Figure 3 - Distributions of deviatoric stresses about a 1.86:1 roadway (σ_1 = 10 MPa)



K = 2.0 K = 0.2

Figure 4 - Distribution of horizontal stresses about a 1.86:1 roadway (σ_1 = 10 MPa)

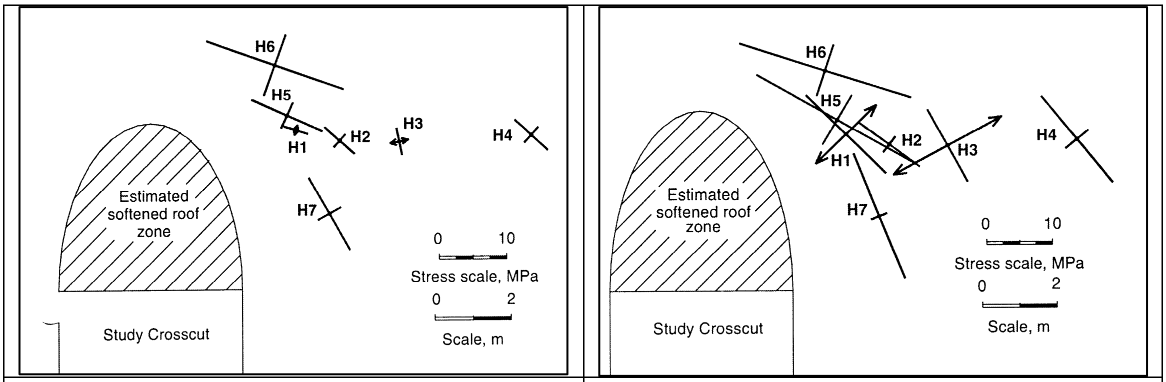
The scale of roof movement and the associated stress redistribution has been demonstrated recently by Mark et al (2007). These authors were able to show that even at less than 20mm of vertical roof movement; the horizontal stresses were already redistributed into an arch over the roadway (Figure 5). This redirection continued as the longwall retreated and the roadway was exposed to maingate stress concentrations.

Further evidence in support of the non-linear redistribution of stresses can be found in the data on stress relieving roadways (Figure 6, Gale and Matthews, 1992). Newton's Third aw requires that the stress relief is also present within the existing roadway. The quantification of roof softening was not available at the time, but experience in the Southern Coalfield is that a bolted roof – not an overall collapse – is adequate to generate the stress relief.

Non-linear stress redistribution is problematical when considering the stresses in the roof during the formation of an intersection. The second roadway is driven in a completely different stress field to that of the first roadway such that the stresses in the intersection roof at the point of breakthrough will be less than those encountered during the straight drivage.

STRESSES INDUCED WITHIN A BLOCKY ROOF

A rock or coal mass is not a continuum and it is possible that its behaviour as a discontinuous medium can significantly modify the stress around an opening. The simplification to rectangular blocks that is possible with coal measure strata allows consideration of two simple analogues.



After development, prior to longwall

After longwall

Figure 5 - Stress measurements at Emerald Mine

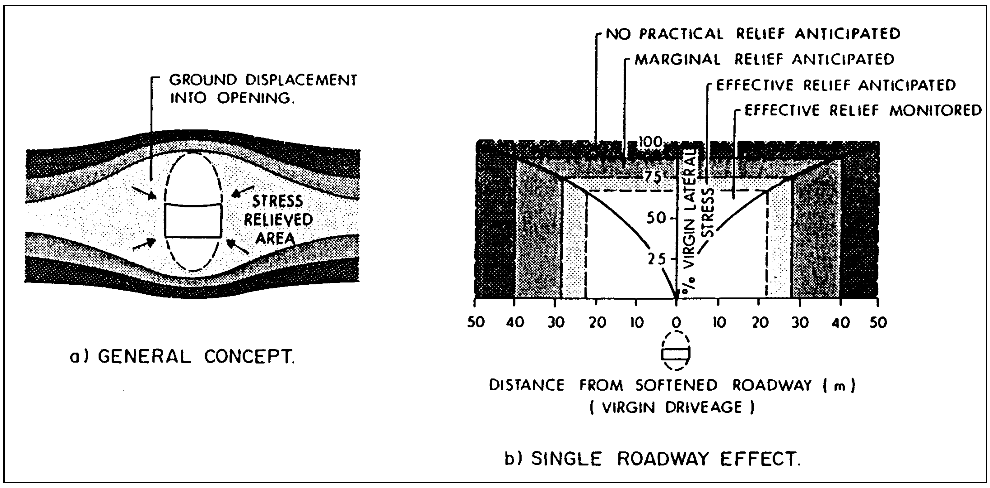


Figure 6 - Concept of a stress relieving roadway

Voussoir beams

The bedded nature of coal measures allows the ready application of the voussoir beam model (Brady and Brown, 1985). The concept is that under situations of no applied lateral force, the incipient rotation of the voussoirs induces a lateral thrust in the beam (Figure 7). The magnitude of this induced lateral thrust depends on the span, density and thickness of the beam. At the point of failure of voussoir beam, the compressive stresses at the roof/rib corner approach the magnitude of the UCS of the rock. An important point to note is that the result of voussoir action is the possible development of compressive stresses at the roof/rib corner together with tensile stresses at the roof centreline. An underground observer may observe the development of a "stress gutter".

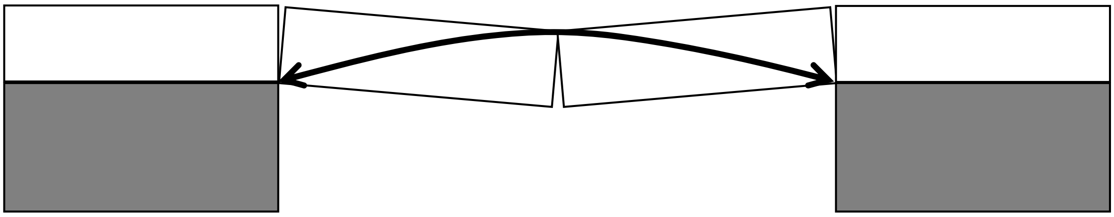


Figure 7 - Voussoir beam deformations induce compressive stresses at the roof corners and tensile stresses at the roadway centreline

Cantilevers

If the roof line is exposed to the onset of tensile stress and there is sufficient relaxation such that the joints dilate, it is possible that a cantilever will develop if joints are widely spaced. The deformation of a cantilever will generate elevated shear/compressive stresses at the roof/rib corner. Once again, there is the possibility of generating compressive failure in a situation of no imposed horizontal stress at the roof line.

OTHER STRESS REDISTRIBUTIONS

If there is differential movement between the two sides of a roadway, the result can be an increase in the bay length of the roof line (Figure 8) and a consequent reduction in the stress acting across the roof (Diederichs and Kaiser, 1999). The scale of this effect assuming the roof line is in the order of 1MPa to 2MPa for a differential compression of 100mm, with a greater reduction for roofs with higher modulus values. This may be significant when it is recalled that the stresses at the roof line after the formation of the roadway may be already low as a result of the stress relief into the goaf and non-linear effects discussed above. A potential location for even large differential movement is when the roadway is bounded by a yielding pillar or coal fender and this is considered to be the basis of the relationship between chain pillar design and tailgate roof support discussed by Colwell (1998). Another situation may be if there is yielding in the floor related to low strength claystone horizons.

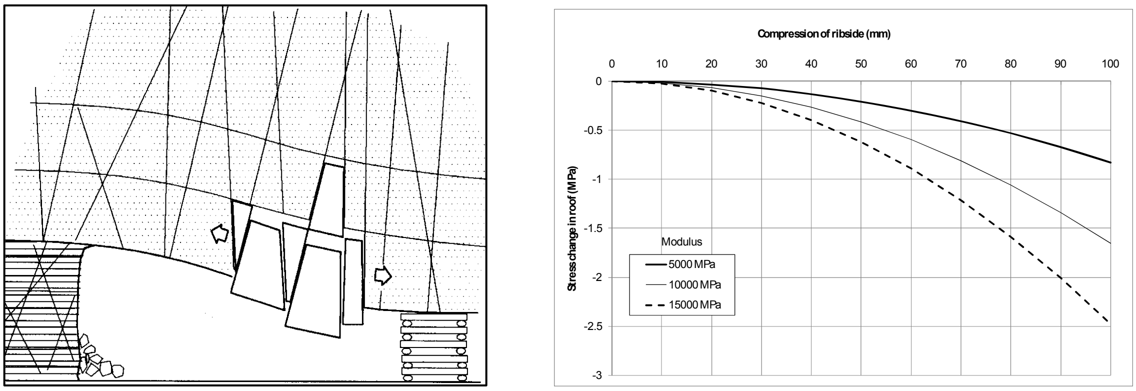


Figure 8 - Relaxation of a roof line as a result of vertical deformation in one of the sides

COMPILED MODEL FOR STRESS IN THE IMMEDIATE ROOF

Based on these previous discussions, the following is a progression through the stress history of the immediate roof of a coal mine roadway. The possible failure modes that may be induced are also included.

At the point of excavation, the reaction to the overburden load is removed and the vertical stresses at the roof line vanish. Until the roof deforms, the horizontal stresses are not yet redistributed. High deviatoric stresses and bedding-parallel shear stresses develop immediately. These stresses may induce stress guttering at the roof corners, either by compressive failure of low strength rock or by the incipient deflection of the roof beams defined by bedding partings that may be present. Simple elastic models can be used to quantify the stresses.

As the mining face advances, say to in excess of roadway width, the roof will have deformed to a 'final state", or in some situations failed if overall compressive failure develops of if the roof layers are too thin and the bolting has not been adequate. In all cases, the horizontal stress in the immediate roof will have decreased to very low values and a "stress arch" developed higher in the roof. Deflections of the bolted roof will generate body stresses associated with the formation of a voussoir beam in the immediate roof (Figure 9). The stresses within the softened zone cannot be quantified but the height of the softened zone can be estimated with simple elastic models.

At the maingate, increases in both the vertical and horizontal stresses around the retreating goaf will alter the stress arch above the roadway and this will lead to an increase in the height of softening. Elastic modes can be used a=to estimate this height. There is no direct increase in the horizontal stress acting in the immediate roof because that roof has already deformed and "softened'. The extra softened material under the stress arch will be an additional surcharge loading on the bolted beam that will then cause an increase in the body stresses within the voussoir arch and an indirect increase in the horizontal stresses at the roof line. This may lead to the onset of stress guttering.

Behind the faceline, the imposed horizontal stresses reduce and the vertical stress increases. The orientation of the principal stress may be skewed significantly off vertical and this could induce some small increases in the height of softening and the stress arch – at the roof line there are no material changes. Evidence from mining operations is that the changes do not induce roof collapses with the current mining geometries.

At the tailgate end of the face, the imposed stress field is now dominantly vertical with a reduction in the horizontal stress due to the presence of the goaf on one side and also behind the faceline. The horizontal stresses within the stress arch may decrease. The horizontal stresses in the immediate roof remain relatively constant and at low magnitudes, unless the chain pillar yields. In the latter case, reaction to the body stresses is lost and the horizontal stresses vanish. Roof collapse may result due to vertical shear along joints or fractures. Localised compressive stresses may develop if the roof structure allows the formation of cantilevers.

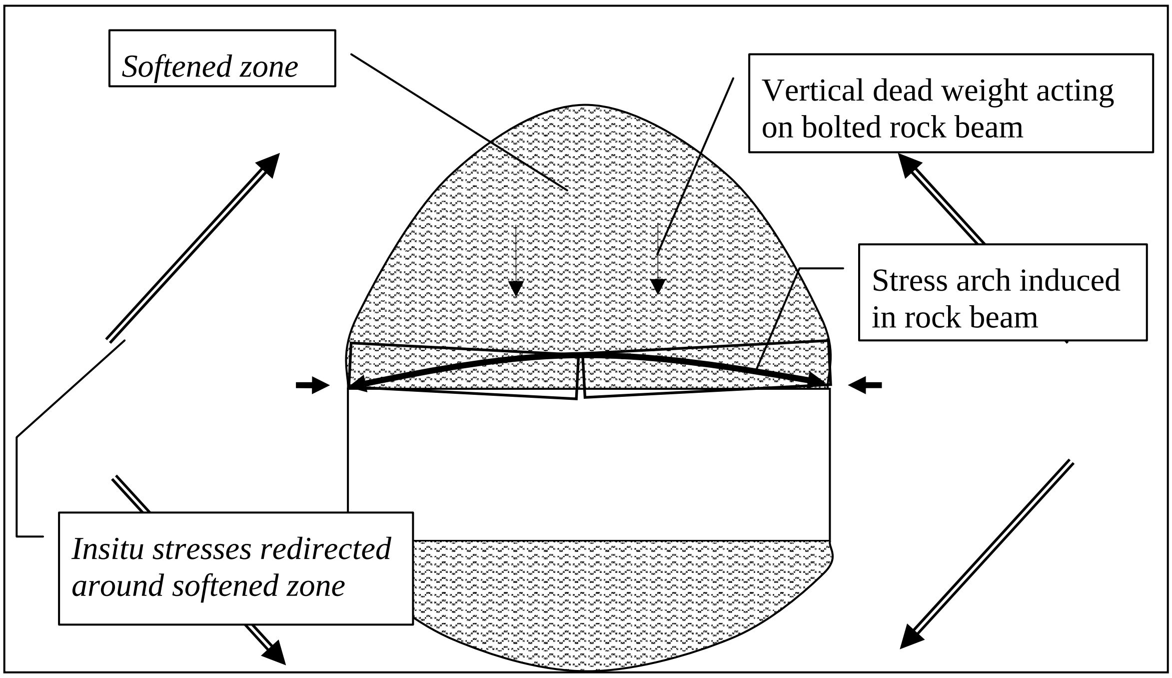


Figure 9 - Redistributed insitu and induced body stresses about a roadway with K >0.8 once the roof and floor deflects.

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