Dissipative structure suppression as a way to increase the sustainable improvement of the frame support bearing capacity

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Abstract. Introduction. A yield frame support is a basic means of providing the underground roadways' stability in the deep mines operating in the hard ground control condition when the ratio of the ground pressure to the unconfined strength of surrounding rock mass exceeds 0.33. The operators adjust the nominal bearing capacity of the frames at 0.55 of their maximum or peak resistance \( F_{\text{max}} \) because the frames operate in a dry friction mode spontaneously generating oscillation, which causes variation of the resistance in the range from 0.1 up to 0.9 of \( F_{\text{max}} \).

Aim/tasks. We intended to reduce the dynamic oscillation of the support resistance that allows for increasing their bearing capacity. Methodology. We used a computer simulation by FLA3D model, indoor testing of the frames, and actual measurements in an underground coal mine.

Results. We revealed a specific behavior of the frame support that reduced the limit of the bearing capacity by 45%. During yielding, the frames generate dissipative structures (DS) that become apparent due to the dynamic nature of stick-slip friction following the yielding process. We demonstrated that DS control and especially its suppression provides a sustainable increase in the frame bearing capacity.

Conclusions. Improvement of the yield frames design and especially their clamps are the prospective way to control DS and provide sustainable enhancement of the frame bearing capacity.

1. Introduction

World mineral resources have been depleted at shallow depth, which is recently increasing progressively due to intensive mineral deposits development. Consequently, geologic and mining conditions deteriorated because the growing ground pressure increased deformation of the rock mass surrounding underground roadways augmenting the tremors and rock bursts. This complicated the roadways maintenance that recent publications highlighted [1, 2].

High level of the stress state in the rock mass surrounding underground roadways at the great depth renewed the relevance of technologies based on the ground pressure relief [3]. Ground pressure diminishes when a roadway support yields and allows essential displacement to occur. As a result, the importance of the yieldable frame supports (YFS) implementation increased especially in coal mines, which extract coal seams at the depth 800 m and more [4–6] where...
ratio of the ground pressure to the unconfined strength of surrounding rock mass exceeds the critical level of 0.33 and negative effects of ground pressure increase dramatically.

Recently, a combination of YFS and rock bolts/cables has become popular [7–9]. YFS consists of several (for example three) overlap segments 1, 2, 3, which are joined with the clamps 4, 5 (figure 1). The clamps grip adjacent segments firmly with the tightening the bolts and nuts. Resilience of YFS is provided due to reciprocal sliding of the adjacent segments. The more the tightening of the bolts the more friction forces are generated in the clamps and joints, hence YFS increases its resistance to the ground pressure.

![Figure 1. Structure of the YFS: 1, 2, 3 are overlap segments; 4, 5 are clamps.](image)

Despite YFS has been designed in 1950s, it still has a great reserve for improvement of the bearing capacity (figure 2). The resistance of YFS periodically varies during its operation while the variation may range from zero up to the maximal bearing capacity of the frame. This capacity YFS demonstrates in the rigid mode of loading when its clamps are blocked. Then YFS starts to deform plastically and transits to a failure state. Such a dynamic oscillation of YFS resistance is nonstationary because the level of the average current resistance drifts during support yielding and peak resistance usually grows as the overlap of adjacent segments expands [10]. An evident illustration of this effect is depicted in figure 2 which presents the results of testing a frame SVP 27. The resistance of serial peaks grew from zero to 202, 252, 294, 336, 365, and 407 kN as the height of the frame reduced by 152 mm. The intermitted line demonstrates an ideal diagram, which would reproduce the maximum of the frame bearing capacity when the adjacent segments slide relatively each other under maximum possible resistance without the drops. After replacing the timeline with a motion scale we may asses energy, which was dissipated by the frame during its yielding. The actual useful work done by the frame was 42.6% of the possible maximum which apparently demonstrates that the reserve of the frame bearing capacity exceeds 50%.

The same tendency has been reported by Pytlik [11]. Eleven tests from 12 demonstrated a steady growth of peaks resistance as YFS was yielding. For example, Pytlik tested LP10/V32 frame having two clamps on every overlap of the frame segments. At the first stage, the frame is tested in the rigid mode with blocked clamps until evident signs of plastic deformation will
appear. In this case, an ultimate load applied to the frame or its bearing capacity $F_{\text{max}}$ was 1069 kN. During the second stage, the frame was tested in the yielding mode, tightening torque in the clamp bolts was 500 Nm which provided permissible load $F_n = 325$ kN.

As Pytlik [11] reported, an initial 100 mm of resilience YFS fulfilled steadily: peaks of the resistance were in the range from 300 to 400 kN whereas minimum counteraction varied about 100 kN. Then consistency of the diagram was broken and the frame transited to a non-stationary mode with a chaotic unpredictable variation of the resistance, which eventually jumped up to 714 kN that is definitely less than $F_{\text{max}} = 1069$ kN. In other words, the probability of the clamp jamming could be neglected. As a rule, YFS is tested until its height reduces by 20% that is in a range from 700 to 800 mm for a frame having cross sectional area from 17 to 20 m². However,
the test was interrupted at 315 mm presumably because of the threatening ascending tendency of the test diagram when initial \( F_n \) increased almost twice as much.

Paczesniowski [12] showed that dynamic and poorly stabilized variation of YFS resistance may dramatically reduce its actual bearing capacity. He calculated index \( k_4 \) as the relation of a permissible load \( F_n \) for YFS to its maximal bearing capacity \( F_{\text{max}} \). The Author determined the percentage of the tested frames, which survived until their vertical deformation reached 20%. Database contained 121 case of YFS indoor testing; 76 frames survived whereas the other 45 frames failed before their vertical size reduced by 20%. The adjacent segments of some frames were blocked with clamps although the first peak of all tested frames resistance matched a predetermined level called ‘permissible load’ that ranged from 0.3 up to 0.8. However, as it was noted before, YFS characteristics is not stationary and its parameters – such as the current peak of the resistance, its variation, and sliding interval between sequential peaks – usually float during testing (figure 2). That is why YFS may eventually fail during testing even if \( k_4 < 1.0 \). According to Paczenoivsky [12], not a single frame having index in the range of \( 0.7 < k_4 \leq 0.8 \) survived. The less the index was the more percentage of the tested frames survived although even the frames having \( k_4 \leq 0.4 \) could fail in the long run as in example of [11] when \( k_4 = 0.304 \ll 1.0 \). The main reasons of this were dynamic oscillation of the frame resistance, stochastic and nonstationary nature of the oscillation. Therefore, aim of this paper was to reduce the dynamic oscillation of the support resistance that allows increasing their bearing capacity and reduces the risk of the failure.

2. Analysis of the YFS resistance oscillation dynamics

YFS operation involves the dry friction mechanism, which is followed by so-called stick-slip auto-oscillation. Stick-slip regime of friction is widely spread in technics [13–15]. Usually, stick-slip friction causes harm producing fretting of the frictional surface and even blocking of the mechanisms. On the other hand, it facilitates accurate positioning [16] in precision machinery. Incorporating dry friction in YFS structure, designers had a goal to reduce cost of the frame supports. In addition, components of the frame are made with high tolerance. Finally, surfaces of the frame components, which contact and slide reciprocally, are rough. All these factors invest in uncertainty of the YFS physical parameters and increase randomness of the friction process. These factors rise the variation of the peak resistance of YFS that should be considered in more detail.

Also, \( F_n \) is determined as the very first peak of a frame resistance. However, it should be borne in mind that the majority of the test diagrams are usually nonstationary and the peaks of YFS resistance show a discrepancy.

We digitized the diagrams of our tests and presented these results in figure 3. The analysis showed that this histogram may be approximated by truncated normal distribution having average of 195 ±131 kN, namely the standard deviation is 67%.

It should be stressed that testing any frame is a time - and labor-consuming procedure because of the big mass and sizes of the frame. Therefore, \( F_{\text{max}} \) is tested one time and an ultimate bearing capacity of YFS is considered as a definite constant. However, constant \( F_{\text{max}} \) does not comply with probability theory. Even extremely simple detail such as a piece of wire has indefinite strength. For example, the ultimate tensile strength of a steel sample variates according to normal law with standard deviation (STD) of 4.38% [17]. However, a frame support is a more complex structure that consists at least of 19 details. Therefore statistical testing of a representative set of the same frame would provide STD at least 10%. Thus \( F_{\text{max}} = 704\pm70 \) kN in our case. Both the normal distributions of the frame in the yielding and rigid modes are depicted in figure 4.

Clearly, these distributions overlap. This does mean that there is a certain risk – several percent in the case – of the frame failure although as far as we know standards of the frame
Figure 3. Histogram of the YFS resistance.

Figure 4. Normal distributions of the frame resistance in the resilient (yieldable) mode and strength of the frame or its ultimate resistance (rigid mode) with blocked clamps.

Testing do not account for the variation of $F_{max}$ and nonstationary property of the test diagram. Paczenovsky [12] proved the risk indirectly demonstrating the negative effect of $k_4$ increase. The diagrams in figure 4 demonstrate how to control the risk. In order to increase the level of acceptable load to a frame, variation of the frame resistance should be reduced. For instance, to lift the acceptable average load from 195 to 300 kN, STD of the frame resistance should be reduced to 75 kN or 25% (intermitted line in figure 4). Simple increase of the tightening in the clamps expands the overlap of the frame resistance distributions in yieldable and rigid modes. Increase of the distributions’ intersection rises risk of the YFS failure and reduces resilience.
interval, shortening the period when the frame survives. So far, the only recognized way to secure and control the survivability of the YFS is to keep $k_4 \leq 0.5$. However, this approach is reactive and not reliable because the frame behavior is not stable during the yielding process that is reflected by the nonstationary test diagram. Our analysis allowed suggesting new proactive tactics to control the survivability:

(i) The most important method is controlling stick-slip friction to stabilize peaks of YFS resistance in resilience mode. This makes yielding of the frame predictable, reduces uncertainty and enforces stability of the process in the predetermined interval of YFS deformation.

(ii) The ideal approach is to suppress stick-slip mode of the friction completely but, in reality, variation of YFS resistance should be reduced as much as possible. Subject to condition (a), this will allow increasing the permissible load over 50% threshold of $k_4$ without raising the risk of surveillance limit reduction.

(iii) Sensitivity of the stick-slip mode to the tightening of the clamp bolts should be minimal. For example, a situation when the stability of YFS behavior depends on the amount of the clamp’s tightening is inadmissible. An increase in the tightening should not impair the stability.

3. Investigation of the stick-slip friction during resilience of YFS

3.1. Selection of the method

Recently, YFS functioning has been mostly investigated using special indoor testing facility \[6,9,11,18–20\]. The most informative data were accumulated from laboratory testing of YFS. All researchers registered the auto-oscillating behavior of the frames during their yielding. They analyzed mechanic energy and heat, which dissipate due to resilient process. Pytlik \[20\] tested YFS under dynamic load. Horst et al. \[19\] demonstrated that corroded frames blocked or loses its bearing capacity. Brodny \[18\] concluded that such components of the clamps as clevises or yokes have crucial impact on functioning of friction joints and safety of YFS operation. We used these findings to substantiate and interpret the resilience of YFS as the stick-slip process, which has the nonstationary nature.

Several researchers carried out underground experiments \[1,21–26\]. Lubosik and Walentek \[22\] emphasized that the most intensive plastic deformation of YFS occurs in underground openings at the great depth especially 1000 m and deeper. Rotkegel et al. \[6\] proved this conclusion and recommended to supply the frames with secondary support such as a ‘spreader’ beam being hung to the cable bolts along a roadway. Wang et al. \[5\] modified YFS implementing tubes filled with concrete instead of traditional U-shape profile.

In recent times, computer simulation became popular to investigate YFS behavior although the problem of friction and reciprocal sliding of the frame segment remains unsolved \[6,27–32\]. Horyl et al. \[28\] simulated by finite element method (FEM) vibration of YFS due to its dynamic loading. Later, Horyl et al. \[29\] managed to simulate explicit reciprocal sliding of the YFS segments and demonstrated by FEM that loading capacity of YFS is proportional to the friction coefficient. This simulation was carried out on a symmetrical half of the profile, and reciprocal sliding of the segments was quasi-static because the researchers did not mention dynamic oscillation of the YFS resistance. In \[30\], Horyl et al. used FEM model that accounted for nonlinear behavior of the frame. However, the Authors managed to trace the first peak of the frame resistance only in limited range of deformation 60-70 mm. Lia et al. \[31\] proposed a new criterion that helped to simulate separation of the arch from the rock exposure, but they did not simulate yield of the clamps as an explicit slide. Rorkegel et al. \[6\] and Mazurek et al. \[27\] investigated stress and bending moment distribution in a frame using FEM but explicit reciprocal sliding of the frame segments remained behind the scope of the research works.
In this paper, computer simulation has been used to investigate the stick-slip friction process during operation of YFS. We used FLAC3D commercial code [33], which enables explicit simulating of irreversible movement and reciprocal sliding in particular. A stick-slip process consists of two phases, namely elastic-plastic deforming that accumulates potential energy in contacted parts of a frame and abrupt relief of this energy, which is followed with its transformation to kinematic one. Indoor testing has demonstrated that acceleration of certain YFS segments may increase at the second stage as much as 2000 m/s\(^2\) [11]. Therefore, operation of YFS is a non-equilibrium dynamic process, which can be described by second Newton law:

\[
\sigma_{ij,j} + \rho b_i = \rho \frac{dv_i}{dt}.
\]  

(1)

where \(\rho\) is the mass-per-unit volume of the medium, \(b\) is the body force per unit mass and \(\frac{dv}{dt}\) is the material derivative of the velocity [33].

Plastic deformation of the frame was simulated using von Mises constitutive model. Contact between adjacent segments and clamps was imitated by special interface (figure 5).

![Figure 5. Schematic of the interface [33].](image)

According to [33] the normal and shear forces describing the elastic interface response are determined at calculation time \((t + \Delta t)\) using the following relations:

\[
F_n^{(t+\Delta t)} = k_n u_n A + \sigma_n A.
\]  

(2)

\[
F_{si}^{(t+\Delta t)} = F_{si}^{t} + k_s \Delta u_{si}^{(t+1/2)\Delta t} A + \sigma_s A.
\]  

(3)

where \(F_n^{(t+\Delta t)}\) is the normal force at time \((t + \Delta t)\) [force]  
\(F_{si}^{(t+\Delta t)}\) is the shear force vector at time \((t + \Delta t)\) [force]  
\(u_n\) is the absolute normal penetration of the interface node into the target face [displacement]  
\(\Delta u_{si}\) is the incremental relative shear displacement vector [displacement]
\[\sigma_n\] is the additional normal stress added due to interface stress initialization [force/displacement]
\[k_n\] is the normal stiffness [stress/displacement]
\[k_s\] is the shear stiffness [stress/displacement]
\[\sigma_{si}\] is the additional shear stress vector due to interface stress initialization [force/displacement]
\[A\] is the representative area associated with the interface node \[length^2\]

The Coulomb shear-strength criterion limited the shear force by the following relation

\[F_{\text{max}} = cA + F_n \tan \phi.\] (4)

where \(c\) is cohesion between contacting parts of YFS.

Itasca introduced a local non-viscous damping to dissipate energy of unbalanced forces, which are produced by dynamic processes [33]. A damping-force term is added to the equations of motion that reads

\[F_{i}^{<l>} + F_{(i)}^{<l>} = M^{<l>}(\frac{dv^{<l>}}{dt}),\] (5)

where \(l = 1, n\)

\(F_{i}^{<l>}\) is the damping force and is given by

\[F_{(i)}^{<l>} = -\alpha |F_{i}^{<l>}| \text{sign}(v_{(i)}^{<l>}),\] (6)

\[\text{sign}(y) = \begin{cases} +1, & \text{if } y > 0; \\ -1, & \text{if } y < 0; \\ 0, & \text{if } y = 0. \end{cases}\] (7)

expressed in terms of the generalized out-of-balance force, \(F_{i}^{<l>}\), and generalized velocity, \(v_{(i)}^{<l>}\). The damping force is controlled by the damping constant, \(\alpha = 0.8\).

We simulated reciprocal sliding of adjacent segments having profile of YFS (LP10/V36 modification). These segments were gripped with SD36W double-yoke clamps (figure 6). In order to exclude additional effect of curvature, we used straight segments of the YFS profile. Such an approach is widely accepted in the practice of YFS testing. Physical parameters of the steel and interfaces are presented in the table 1.

| Metal        | Interface | Metal        | Interface |
|--------------|-----------|--------------|-----------|
| Bulk modulus, Pa | Shear modulus, Pa | Yield strength, Pa | Normal stiffness, N/m³ |
|              | Shear strength, Pa |                 | Shear stiffness, N/m³ |
|              | Friction coefficient, degree |                 | Cohesion, Pa |
| 140 * 10⁹ | 84 * 10⁹ | 550 * 10⁹ | 26 * 10⁹ |
|              | 26 * 10⁹ |              | 13.0      |
|              |          |              | 5.0       |

Table 1. Physical parameters of the simulated YFS.
3.2. Substantiating of boundary conditions

According to previous experience, all researchers loaded an experimental frame with hydraulic rams, which have been anchored in a base that was another big frame surrounding the tested frame. These loading facilities have essential elastic resilience. Besides, the hydraulic system serving the testing facilities had limited capacity. Therefore, pliability of the loading facility is commensurate with the tested frame flexibility, and they influence each other. By default, indoor testing of YFS is considered as in a set load mode, although the real loading facility cannot keep the stable load. Furthermore, amplitude of YFS resistance variation can be overestimated during indoor testing.

Rigidity of the surrounding rock mass strongly depends on geologic structure and physical properties of the rock. Thus, behavior of YFS may variate essentially depending on the surrounding rock properties. Anyway, it may be expected that soft surrounding rocks will apply more stable load to YFS in comparison with hard rock mass, which may accumulate essential amount of potential energy. However, real boundary conditions applied to YFS in an underground roadway are worse than those in a laboratory are because laboratory facility provides minimum of degrees of freedom. That is why YFS demonstrates the most efficient behavior and dissipates the maximum external energy due to friction of the overlayed segments in
a laboratory. In the real environment of an underground roadway, YFS may dissipate the energy of ground pressure not only because of friction mechanism but also due to plastic deformation that reduces integrity and the bearing capacity of the frame. Finally, there is uncertainty in this problem and the best way to solve it is to choose a simple and definite boundary condition.

Therefore, we fixed the protruded end of the segment 2 and applied constant velocity to the opposite end of the segment 1 (figure 6). This velocity was selected at 0.001 so that damping algorithm kept up with the dissipation process. To end with, we tested YFS in a set displacement mode. Pretention of the bolts in the clamps was varied in the range from 200 to 400 MPa to prevent plastic deformation of the bolts.

As has been said earlier, an indoor facility limits the degrees of freedom to the minimum that provides a favorable condition of YFS testing, hence it usually demonstrates maximum of bearing capacity.

4. Results of simulation
Testing of YFS in the set displacement mode provides movement of the rear end of segment 1 with constant velocity that should provide a smooth sliding of the segment 1 relatively segment 2. As a result, we should not have expected an apparent variation of the YFS fragment resistance. Nevertheless, we registered a periodic oscillation of unbalanced forces in the whole model during YFS fragment test (figure 7).

Two evident modes of fluctuation may be noted, namely low and high frequent. We consider the high frequency oscillations as those having stochastic nature because our model consisted of 1976 zones and 4228 nodes. Kinematic energy of the dynamic interaction among the zones and nodes during sliding movement dissipated according to (5), (6), (7) and the frequent oscillation of the unbalanced forces may be explained by error of calculation based on float numbers rounding. However, low-frequency oscillations are natural, should be qualified as an effect of self-organization, and addressed to the stick-slip mode of friction. Seventeen low-frequency fluctuations were registered during sliding of segment 1 to 0.4 m. As a result, the average step of the oscillation was 23.5 mm along sliding direction, which falls within the experimental range from 2.9 mm [20] to 37.5 mm [11]. The diagram in figure 7,a demonstrates the dynamic of reciprocal segments friction for the pretension of the clamps’ bolts to 300 MPa, whereas fragment (b) of this figure shows the diagram for the tightening of the bolts to 400 MPa, whereby the bolts transited to plastic state at the end of the experiment. The average level of the unbalance forces grew 1.46 times in the second case that corresponds to a common sense and matches the results of simulation by Horyl et al. [29].

5. Possible ways to control the stick-slip friction in YFS
The great number of conventional clamps are used in the industries and it is expedient to maintain the YFS reliably. Physical methods have been proposed and tested to suppress the stick-slip using vibration [34]. Another approach to damping the stick-slip regime is implementation of a deforming sliding layer [35].

Chemistry proposes different means, which might eliminate stick-slip friction. Spraying of an inhibitor on the surface of YFS profile can reduce their adhesion [31]. Friction coefficient can be reduced at the stick spot using surfactant [36]. Such treatment of the YFS profile surface may be done by separate sections remaining gaps between them. Those sections, which have been treated, will carry out stabilizing function in order to keep the yielding process in the stationary mode. Parameters of this technology such as width of the sections, intervals between them, chemical components are the subject of the future investigation.

A method should be developed to forecast and reveal the moments when an individual YFS is going to stick at the dangerous threshold of its resistance. A single peak of the YFS resistance can damage the whole frame. This is expedient to diminish the resistance at some limited intervals
Figure 7. Unbalance force diagrams: (a),(b) – tightening of the clamps to 300 and 400 MPa correspondingly.

in order to save YFS bearing capacity during its yielding through the whole working range, namely 20% vertical deformation of the frame and might be more. YFS main duty is to control ground deformation around the underground opening but not to prevent it. Synchronous radial irreversible movement of the ground inevitably causes self-wedging effect when discrete adjacent pieces of the surrounding rock mass block and jam each other [37]. This behavior generates a self-supporting effect [38] resistance of which is by two orders more than YFS resistance.

6. Conclusion

The standard of YFS survivability testing envisages comparison of maximal resistance of the testing frame in predetermined yielding range and the ultimate bearing capacity of the frame previously tested in the rigid mode with blocked clamps. YFS operates on the principle of the dry friction in the stick-slip mode and the frame are made with high tolerance, surfaces of the frame components, which contact and slide reciprocally, are rough. All these factors invest in the uncertainty of the YFS physical parameters and increase randomness of the friction process.
These factors rise the variation of the peak resistance of YFS and frequently change the steady friction to non-stationary auto-oscillation process. To account for this uncertainty, we introduced the natural variation of the ultimate strength of YFS and matched two distributions, namely normal distribution of the ultimate strength of the frame, and truncated normal distribution of the frame resistance. Such an approach facilitated not only to reduce the uncertainty but assess the risk that the tested frame fails. So far, the only recognized way to secure and control the survivability of the YFS is to keep $k_4 \leq 0.55$. However, this approach is reactive and not reliable because the frame behavior is not stable during the yielding process that is reflected by the nonstationary test diagrams. Our analysis allowed suggesting new proactive tactics to control the survivability:

(i) The most important method is controlling stick-slip friction to stabilize peaks of YFS resistance in yielding mode. This makes yielding of the frame predictable, reduces uncertainty and enforces stability of the process in the predetermined interval of YFS deformation.

(ii) The ideal approach is to suppress stick-slip mode of the friction completely but, in reality, variation of YFS resistance should be reduced as much as possible. Subject to condition (a), this will allow increasing the permissible load over 55% threshold of $k_4$ without raising the risk of surveillance limit reduction.

We used FLAC3D commercial code to investigate the stick-slip friction process in the set displacement mode during operation of YFS. Validation of this model has shown that results of our simulation are not in contradiction with the independent computer simulation and indoor experiments. We simulated reciprocal sliding of two straight overlapped segments of YFS profile, which were gripped by two clamps. Despite we applied constant velocity to the rear end of the moving segment, certain dissipative structures emerged, which appeared as spontaneous auto-oscillation of the unbalanced forces in the model. We proposed new design solutions, methods and technologies to control the stick-slip friction process increasing the bearing capacity and reliability of YFS.

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