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ESTIMATING IMPACT FORCES OF FALLING ROCKS IN MINE SHAFTS

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Abstract: Miners working in mine shafts have to be protected from objects that can fall and cause injuries. Falling object protective structures (FOPS) such as bulkheads, structural enclosures and canopies are commonly constructed in the mining industry as protection. The design of these structures is challenging since one of the main parameters, namely the magnitude of the load imposed on the structure, is unknown. Therefore, the most difficult assumption is the determination of what is falling down the shaft. To aid in this, the designer has to rely on information from sites and the experience of mine personnel. There is limited information available in the published literature on falling rock impacting part of a protective structure or impacting a rock surface at shaft bottom. The estimation of the impact force is the important element of any rational design. A simple procedure to quantify the impact force on a FOPS, based on energy balance principles is presented in this paper. The proposed method includes consideration of fragmentation of the falling rock. A design criteria, based on impact energy levels, is proposed. To illustrate the suggested design approach, an illustrative example is presented.

1 INTRODUCTION

In the mining industry the safety of miners is of paramount importance. One critical area of work is shaft sinking. During maintenance work, in the shaft or at the shaft bottom, miners have to be protected against objects that can fall down the shaft. The falling object protective structure (FOPS) could be a canopy at a shaft station or on a sinking work stage, bulkhead in the shaft or a protective structural enclosure at the shaft bottom.

In order to properly provide a structure, the designer needs to know the geometry, material of construction and external loading. Of these requirements the loading is the most problematic since the falling object is usually not known as to its size, shape and height of fall. Simply stated, one cannot provide protection from a falling object if its properties are not known. Theoretical assumptions sometimes are not helpful and therefore site observations, accident reports and other available site data are of great importance. Protective structures are commercially available, but their certified strength is often based on assumptions of the falling object that bears little resemblance to reality. There is little information available for structures subject to falling objects in mine shafts, specifically rocks falling on a structure or on rock at shaft bottom. Giacomini et. al. (2009) have examined experimentally rock falls and presented some useful general comments on the topic. Their study offers

a general approach to rock falls, including fragmentation of rock at impact on a rock surface. The resulting data is however site specific, i.e. some specific rock types were studied.
The present paper will use some of the concepts of Giacomini et. al. (2009) and combine them with the proposed method of Haydl (2017) to obtain approximate solutions to the problem of falling rocks on structures and rock bases. An attempt is also presented here to explore the problem of rock fragmentation on impact. Prediction of rock fragmentation is important since it impacts the safety of miners. A design criteria and design limits are proposed for impacted structures. Illustrative examples are shown for the proposed design method.

2 BASIC IMPACT CONCEPT

The impact problem can be formulated in terms of an energy balance (Meriam 1955), i.e.

[1] $\frac{1}{2} P D = \frac{1}{2} m v^2$ (or "m g h")

The left side of this equation represents the energy absorbed by the impacted structure, whereas the right side is the energy of the falling object just before impact. The parameters are defined as

P = the impact force
D = deformation (sum of impacted and impacting object)
m = mass of falling object
g = gravitational constants, 9.81 m/sec^2
v = terminal velocity of falling object
h = height of falling object drop

"Eq. 1" contains two unknowns, P and D, therefore the equation cannot be solved directly as it stands. There is an infinite number of combinations of P and D that satisfy this equation. The correct solution is when the actual product of P_0 and D_0, as obtained from the analysis of the structure, matches the right hand side of "Eq.1" (Point A in Fig.1).

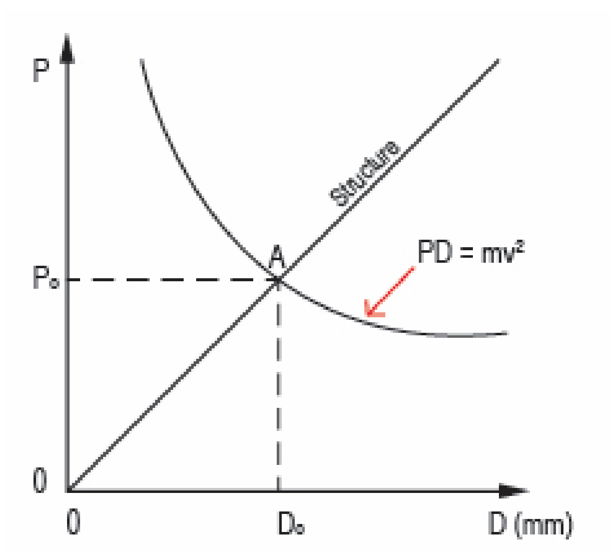

Figure 1: P vs. D

The impact problem can also be approached from the impulse vs. momentum principle (Meriam 1955), namely impulse equals change in momentum:

[2] $P\,t = m\,v$

where t = the time span of impact

The two unknowns P and t make this equation unsolvable. It seems to be a common mistake by designers (private communications) to arbitrarily select a time of impact t, then evaluate P and present the solution as valid. The value of impact force P obtained in this manner seldom bears any resemblance to the actual force. The correct solution consists of obtaining P from "Eq.1" and then calculating the time of impact t from "Eq. 2".

3 IMPACT ON FOPS IN MINE SHAFTS

The general approach to the problem of rock falls (Giacomini et.al.2009) can be applied to formulate a method of estimating impact forces on FOPS. Consider the energy balance

[3] $E_b = E_f + E_a + E_D$

Here

$E_b = \frac{1}{2}\, m\, v^2$, the energy of the falling object just before impact

E_f = the energy to fragment the falling object

$E_a = \frac{1}{2} \sum m_a (v_a)^2$, the energy of the fragments after impact

$E_D = \frac{1}{2}\, PD$, deformation energy of falling and impacted object

Modifying "Eq.3" by substituting these parameters one obtains

[4] $\frac{1}{2}\, P\, D = \frac{1}{2}\, m\, v^2 - E_f - \frac{1}{2} \sum m_a (v_a)^2$

This energy balance equation states that the impacting energy is reduced by the value of the fragmentation energy and the energy of the fragments. Note that if the impacting object does not fragment, this equation reverts back to "Eq.1".

4 IMPACT FORCE ESTIMATE

There is little information available in the published literature on impact of rocks on FOPS or rock surfaces. This topic has however received some attention recently. A paper by Giacomini et.al.(2009) gives results of an experimental program about rock falls and also examines fragmentation of falling rocks. For lack of any other available sources we shall make use of this publication and attempt to expand on the concepts and results as they apply to estimating impact forces on FOPS.

Consider the vertical impact of falling objects on a FOPS. Giacomini et. al. (2009) use the concept of "restitution coefficient k" , as formulated in a study by Pfeiffer et.al. (1989). This factor is basically a reduction or damping factor applied to the impact velocity. This coefficient as applied to the impact velocity results in the after impact velocity v_a , i.e.

[5] $v_a = k\ v$

4.1 Case of no Fragmentation

In this case the fragmentation energy $E_f = 0$ and "Eq. 4" is modified to

[6] $E_{a\ (mod)} = ½\ m\ (k\ v)^2 = ½\ P\ D$

which is the energy of the intact falling object after impact.

In this equation the coefficient k acts as a reduction factor applied to the vertical impact velocity. Substitute "Eq.5" into "Eq.1", one obtains

[7] $E_{D(mod)} = E_b – E_{a(mod)} = ½\ m\ v^2\ (1 – k^2\ ) = ½\ PD$

4.2 Case of Fragmentation

"Eq. 4" makes it possible to estimate the impact force of a falling object on a FOPS or rock base. The unknowns are the energy of the fragments after impact and the energy to fragment the falling rock. In (Giacomini et.al.2009) impact experimental results of two rock types impacting a hard rock surface are reported. The rock types used in the experiments were Beola and Serizzo from the Ossola Valley in Italy. We shall use these results and apply them to the FOPS problem.
The results were as follows:
The ratio of fragmentation energy to impact energy was

[8] $E_f / E_b = 0.13$ to 0.60 , for $k = 0.4$ to 0.8

This ratio did not vary significantly with the number of fragments. The ratio of energy after impact to the impacting energy was

[9] $E_a / E_b = 0.02$ to 0.155

4.3 Impact Force

When these ratios are alternately inserted into "Eq.4" , using "Eq.5", upper bound values for the deformation energy ½ P D are found to be

[10] $½\ P\ D = 0.42\ m\ v^2$ if no fragmentation occurs, and

[11] $½\ P\ D = 0.36\ m\ v^2$ if fragmentation takes place

These equations are proposed to be used in predicting approximately the impact force of a falling object on a FOPS. The method and procedure to calculate the maximum impact forces outlined in detail in (Haydl 2017).
Note that the experiments in Giacomini et.al.(2009) were not able to quantify an energy level at which fragmentation would occur. It would make sense then to conservatively design a FOPS for the impact force obtained from "Eq.10" and "Eq.11".

The above upper bounds indicate that there is not a significant reduction in the impact energy for design purposes. It is therefore important to obtain experimental verification of theoretical results.

5 DESIGN CRITERIA

It is of interest, and as a guide to designers and engineers, to propose a design criteria for the present topic. In contrast to accepted engineering practice of applying a safety factor to the results of an analysis/design, in the present application the proposed approach to safety is different. Since the unknown parameters are the size, shape, height of fall and the rock properties, the design criteria should be based on a concept of safety. Therefore, the procedures, sequence of events that are expected and the exposure to falling objects has to be considered. This will require a risk assessment of the project. As a companion to this and depending on the results of the risk analysis, a design category can be specified. The category classification can then be used to determine the safety margins of the design.

It is noted that design standards by others (SAE 1981) and (ISO 2005) recommend design limits expressed as impact energy levels and not as stress levels. As an example Table 1 has been prepared to indicate a possible criteria for designing FOPS.

Table 1

Design Category	Impacting Energy	Probability of Occurrence
1	≥ 135 KN.m	high
2	70 to 135 KN.m .	moderately high
3	7 to 70 KN.m	moderate
4	0 to 7 KN.m	low

In addition to this classification, stress and deformation limits need to be established. It is proposed to use as stress limit the yield stress of the impacted structure or its components. In a typical protective structure the most vulnerable member should be analyzed. In many cases plastic deformations will be the result of the impact. To estimate these the reader is referred to Haydl (2017) for estimating plastic deformations. The designer also must ensure that calculated deformation in some members do not lead to collapse of the entire structure.

6 CONCLUSION

This paper makes an attempt to expand on the basic concepts of rock falls, presented by Giacomini et.al.(2009), and apply them to the problem of falling rocks in mine shafts. The main problem is the fact that one does not know what is falling down the shaft. It is therefore difficult to propose solutions for the safe design of FOPS.

In the preceding the information from Giacomini et.al.(2009) was used to obtain upper bound estimates on impact forces in order to obtain worst scenario quantitative results. The proposed approach to solving the title problem is based on basic principles, namely energy balance. In this proposed approach the main difficulty arises from the fact that there are a number of unknown parameters that have to be

assumed. These parameters are subject to wide ranges as shown in Giacomini et.al (2009). For a lack of any other information these parameters are used to estimate the impact force of falling objects.
It is questionable that a general theory can be formulated for the title problem and one is left with a piece wise approach which will differ for each project.

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APPENDIX

Numerical examples are presented to illustrate the method of this paper to estimate impact forces on FOPS.

Example 1

Consider that a simply supported beam W360x101 of length L= 6.1 m is impacted by a rock of weight 22.7 kg falling from a height of 30.5 m. Find the max. stress and max. deflection of the beam.
The mass of the rock is
$m = W/g = 0.023$ KN sec^2/m
The impact velocity is
$V^2 = 2gH = 598.4\ m^2/sec^2$
Assume that fragmentation of the rock does not occur, then "Eq.10" applies and the impact energy is
$½ P D = 0.42\ m v^2$, then
$P D = 0.84 \times 0.023 \times 598.4 = 11.56$ KN m
The deflection at the center of the beam is
$D = P L^3 / 48 E I$, substituting this into the above equation results in
$P^2 L^3 /48 E I = 11.56$ KN m
Solving first for P = 384.3 KN and then for D = 0.030 m
The bending moment at the beam center is
$M = P L/4 =586$ KN m and
The max stress is F = 347 MPa.

Note that the design impact energy can also be found from Fig.2 as the area within the triangle 0AB and is

$E_b = ½ PD = 384.3 \times 30 \times ½ /1000 = 5.78$ KN m

In this example the estimated response of the beam is elastic, if we consider the material to be $F_y = 350$ MPa.

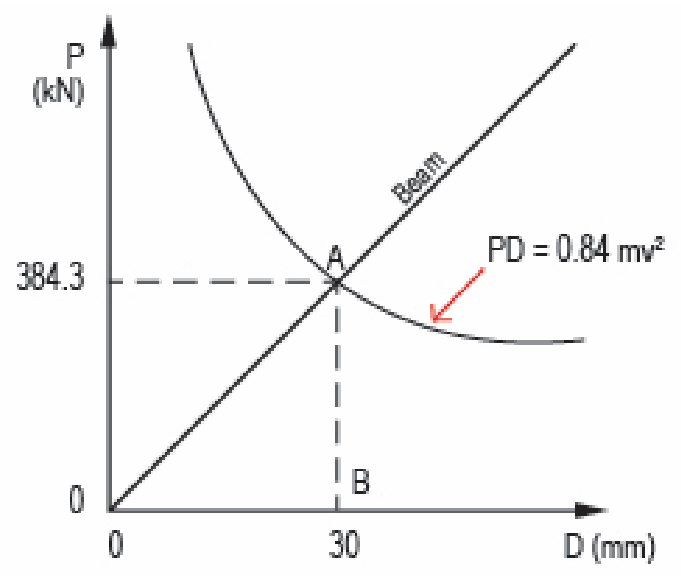

Figure 2: Example 1, P vs. D

Example 2

A protective structure consisting of a beam grillage, covered with a steel plate, has a main beam W460x74. Assume that a rock of 45.5 kg falls from a height of 38.1 m, impacts the middle of the beam and fragments into an unknown number of pieces. A computer model of the structure has been created. A load of 1112 KN is applied to the beam model and the results show a 38 mm deflection under the load and a bending moment of 1085 KN m (Fig. 3)

The mass of the falling rock is

$m = 0.046$ KN sec^2/m

The impact velocity is

$v^2 = 2gh = 747.5$ m^2/sec^2

The design impact energy is ("Eq.11")

$½ P D = 0.36 m v^2 = 12.38$ KN m and

P D = 24.75 KN m
Point A in Fig.3 is found by trial as P = 845 KN

The bending moment if found by proportion

M = 1085 x 845 /1112 = 825 KN m

The corresponding stress is

F = 565 MPa ≥ 350 MPa (the assumed yield stress)

The beam sees plastic deformation and the yield load is

P_y = 845 x 350 / 565 = 523 KN

The corresponding moment is M = 511 KN m

The plastic deflection can be found from the energy balance as the areas in Fig. 3, namely area 0AE = area 0BCF

½ x 845 x 29 = 523 (D_p – 9) with the result that

D_p = 33 mm deformation

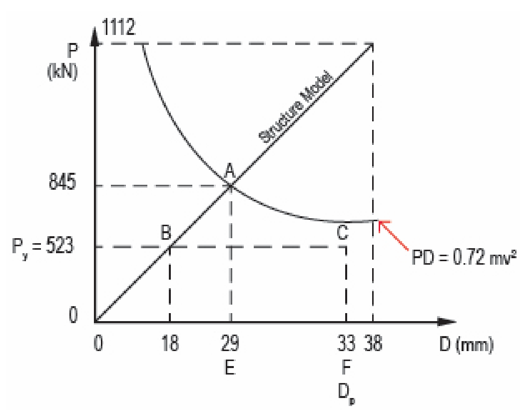

Figure 3: Example 2, P vs. D