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THE UNIVERSITY OF OKLAHOMA / NORMAN / 10-12 JULY 1991

Rock Mechanics as a Multidisciplinary Science
Proceedings of the 32nd U.S. Symposium

Edited by

JEAN-CLAUDE ROEGIERS

School of Petroleum & Geological Engineering, The University of Oklahoma, Norman

OFFPRINT

A.A.BALKEMA / ROTTERDAM / BROOKFIELD / 1991

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Rock Mechanics as a Multidisciplinary Science, Roegiers (ed.)
© 1991 Balkema, Rotterdam. ISBN 90 6191 194 X

Perforation stability – Physical and numerical modelling

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Abstract: This paper presents the results of a study into the mechanical stability of wellbore perforations. Numerical and physical models of the main factors associated with a borehole and perforations were generated and subjected to various load regimes. The results show the effects of the main parameters on the overall stability of the structure and the implications to productivity.

1 INTRODUCTION

Perforations are the flow channels which conduct fluid between the reservoir and the wellbore. Factors related to the formation and the perforation design combine during the creation process to produce perforations with flow capacities below that which is theoretically possible.

Many studies have been conducted on charge and gun performance (Saucier and Land, 1980, King et al, 1986, Halleck et al, 1988), casing damage (Bell and Shore, 1980, Pattillo and Smith, 1983), perforating techniques and conditions (Bonomo and Young, 1983, Aaron Cheng, 1985, Halleck and Deo, 1987, Regalbuto and Riggs, 1988) and on the nature of flow around and into the perforations (Harris,1966, Bell et al,1980, Klotz et al, 1980, Hong,1975). The problems of perforation stability have, in the main, concentrated on the effects of high flow rates through perforations and the stability of perforations in friable and weakly consolidated formations (Locke, 1981, Tariq et al, 1981 & 1987, Deo et al,1987, Stewart, 1987, Vriegen et al, 1975, Antheunis et al, 1976, Morita et al, 1989). However, the interaction between the borehole and the perforations as a structure within the rock mass, and the material properties of the rock mass must be considered in the design of a perforating system.

The borehole and the perforations will redistribute the earth stresses within the rock and cause local deformation. If the ultimate strain is not exceeded, the rock will deform elastically. However, if the ultimate strain is exceeded, the overstressed region will be deformed plastically and may collapse. Operationally, the majority of perforations are created by shaped charges which generate pressures in excess of the strength of the formation. This develops a compacted zone around the perforation tunnel. This study was limited to the deformation of the perforations after creation, and does not include the effect of viscous flow into the perforations.

2 MODEL DESCRIPTION

The study examined the following material and structural properties:
1. Perforation length, diameter
2. Shot density and phasing

3. Rock material properties
4. Rock stresses, including pore pressure
5. Rock failure criteria (elastic or elasto- plastic)

Physical and numerical models were developed and an extensive material testing programme provided data for both types of models. The physical models tested various geometries and loading regimes to enable realistic numerical models to be developed. The physical models were tested dry at atmospheric pressure.

2.1 Physical models

The physical models consisted of two types: blocks and hollow cylinders. The blocks were sandstone with laboratory tensile and uniaxial compressive strengths of 3.0MPa and 29.0MPa respectively. The dimensions were 457mm by 305mm by 305mm, with a 127mm diameter hole cored in them to represent a wellbore. They were then split along the axis of the hole to provide two half boreholes. Holes 12mm in diameter were drilled from the borehole wall into the block at various shot densities and phase angles to represent the perforations. One sample was prepared with a section of steel pipe to represent a cased and cemented borehole. Twelve blocks were tested under uniaxial compression within a servo- controlled stiff testing machine. A plot of axial load against axial deformation was produced to indicate the onset of failure of the block. A two arm caliper was devised to measure the diametral deformation of the perforation. Three were made and they consisted of two steel arms braised to a block of steel. A strain gauge on the arm measured the deflection, and all the calipers were calibrated regularly. They were oriented within the perforations to measure vertical displacement as it was expected that failure would initiate at the sides of the perforations. This was the case for the first block tested and it was reasonable to assume the succeeding cases would be similar. The dimensions of the perforations and of the block precluded development of an instrument to measure the horizontal deformation and the depth of the fractures produced.

The blocks were loaded until they failed. Measurements were taken at regular load increments and the development of fractures within the borehole was photographed. After failure, the debris from the block was collected for sieve analysis and the perforation tunnels were cut axially to examine the fracture. A net of the borehole fractures was produced.

The hollow cylinder models were 110mm long, 55mm diameter with a 25mm diameter hole located coaxially within the core. Perforations were drilled through the cylinder walls at different shot densities and phasing angles. The cylinders were confined in a triaxial cell which was located within the testing machine. Both confining stress and axial load were applied by servo- controlled hydraulics. Small calipers were devised to measure diametral deformation of the perforations. A hollow platen was produced through which the electrical leads of the strain gauge were brought out of the hollow cylinder. 36 specimens were tested to failure at different confining pressures of 50, 100 and 150bar. At each successive axial load increment, the extent of the fractures within the cylinders was estimated visually, through the hollow platen. After failure, the debris was collected and sieved. The cylinders were cut axially, the extent of the fractures logged, and a net produced of their orientation around the borehole.

For both physical models an extensive rock properties testing program was run to determine strength, modulus of elasticity, Poisson's ratio, angle of internal friction and apparent cohesion.

2.2 Numerical models

A commercial finite element package, LUSAS, was used to model the perforations. Before the final model geometry was chosen, a number of preliminary models were run to ensure compatibility with the results of the physical models. The models were two dimensional: a section along the length of the perforation from the borehole into the reservoir, and a section across the diameter of the perforation. The diametral sections were modelled by octahedral and circular profiles.

The model represented a vertical section of 305mm and a depth from the borehole into the formation of 381mm with perforation lengths of 76mm to 305 mm. The shot densities varied from 1 to 6 shots per foot, phasing angles of 0° and 90° with inline, inplane and spiral patterns. The perforation diameter was varied between 6.35mm, 12.70mm, 19.05mm and 25.40mm.

The following assumptions were made :

1. The rock is either linear elastic or elasto- plastic, homogeneous, isotropic
2. Plane strain conditions prevail
3. The perforation is considered to have failed when the rock around the perforation begins to fail
4. The depth of the perforated interval is 3048m
5. The overburden pressure gradient is 22.1kPa/m and the formation pressure gradient is 10.2kPa/m
6. The perforation length is measured from the cement rock interface into the formation
7. Compression is negative and tension positive.

Fluid flow was not modelled, however, pore pressure within the formation and completion fluid pressure within the perforation was modelled. This altered the effective stress around the perforation. The borehole was cased and cemented.

3 RESULTS

In general, the results of the physical and numerical models agree. The physical models showed that there is a complex interaction between the redistributed stresses around the wellbore and the perforation. The perforation diameter decreases with increasing applied stress and the perforation tunnel was seen to deform and spall at the sides, the debris collecting within the perforation. The deformation mechanism appears similar to borehole breakout. The top and bottom of the perforations had deformed but had not failed. Table 1 and Table 2 summarise the results of the modelling. The numerical models were run for each parameter configuration and the results related to the failure load.

3.1 Stress and strain distribution

Figures 1, 2 and 3 show typical stress distributions along the perforation and across the diameter. The deformation of the models depends on several factors as previously stated. The deformation was greatest at areas under the effect of the greatest redistributed stress around the perforation tunnel and the intersection of the perforation tunnel and the cement rock interface. The stress around the perforations reduces to normal levels at 12mm from the perforation tunnel.

The deformation around shot densities greater than 4 shots per foot indicates the development of a plastic zone. The extent (10.8mm- 15.9mm) depends on the stress concentration which is greater for perforations which are in closer proximity, that is the in-line and in-plane geometries.

3.2 Perforation deformation

The caliper results indicated that the perforation diameter decreased asymptotically as the load applied increased. Figure 4 shows the relationship for one perforation, which can be expressed by the following general equation:

$$D_{ave} = D_i - j(\sigma_v) - m \ln(\sigma_v)$$

where D_{ave} is the average diameter, D_i is the initial diameter, σ_v is the vertical stress and m and j are factors which depend on the particular geometry of the structure. The interaction between the geometry and the stress dictates the change in perforation diameter. For the most part the deformation was the result of elastic strain which was relieved if some other part of the structure failed. The spiral patterns showed the greatest reduction in perforation diameter in the elastic structure.

3.3 Fracture development

The orientation and direction of the fractures which developed were complex. The perforation tunnels were seen to fracture at the sides, initiated at the cement- rock end. Both the numerical and physical models showed failure initiating at the cement rock interface. The fractures grew along the perforation tunnel as the load was increased, either by direct application of load or by interaction between the perforation and the borehole. They resemble borehole break out fractures.

The borehole wall also failed at higher stress levels. This produced conical shear fractures around the borehole generating large blocks of material. The interaction between the borehole and the perforations generated break out fractures on the surface of the borehole, extending from perforation to perforation. The fractures were of variable length and ranged from 3.15mm to 22.10mm in width. the depth ranged from 0.06mm to 8.10mm. The debris produced was sieved and produced a normal size distribution for the sandstones tested. The amount of debris was related to the fractures produced and the stability of the structure. It is significant that increasing the shot density by a factor of 2 increased the debris produced by a factor of 8.

3.4 Perforation system stability

The stability is the overall effect produced by the interaction of the perforation and borehole geometries with the rock stresses and in this study, was simply related to the failure load of the structure. In general there appeared to be 2 distinct modes of deformation. That which occurred below the failure load and that which occurred during and after failure.

Below the failure load of the structure, there were local fractures created at the sides of the perforation tunnels and at the end of the perforation adjacent to the borehole. The extent of these fractures appears to be related to the magnitude and location of the redistributed stresses. The fractures appear to grow only during an increase in the applied stresses. These conditions generate the greatest reduction in perforation diameter.

The length of the perforations, the shot density, shot phasing and shot pattern also affect the fractures produced. As the shot density increases, the stability decreases in that the interaction between the individual perforations increases the redistributed stresses.

The phasing and pattern affect the stability. An inline pattern of 0 ° phasing produced the least stable configuration. An in-plane pattern, irrespective of the phasing , produced a more stable configuration and a spiral pattern, of various shot phasing produced the most stable configuration. The important feature appears to be the interaction between the perforations and it was recorded that failure of an in-line pattern did not occur in all of the perforations at the same applied load. This can be considered in terms of a failed region in one perforation redistributing the load farther into the rock mass and shielding the adjacent perforations. This concept is used in mine planning to drive new tunnels in destressed zones

After massive failure of the structure, large fractures were produced at the borehole wall. The block models showed a decrease in axial stress at failure, but the block was still capable of being loaded. In this condition, the perforation deformation was reduced. Only one sample represented a cased hole and the results showed an increase in the failure load, however, the perforations and the borehole wall still fractured.

4 CONCLUSIONS

The study has shown that the deformation of a perforated borehole due to applied rock stresses is complex. Failure to consider the structural stability as an integral part of the perforation design may lead to lower than expected productivities, and attribute the cause to some other aspect of the operation.

Consideration must be given to the interaction between the perforations and the borehole. The results show the formation of fractures within the perforation at loads below the failure load of the rock mass or below the loads which cause borehole stability problems.

Within the perforations, local failure is initiated at the entrance of the perforation and is extended as shear fractures along the sides of the perforation tunnel as the applied load is increased.

The fractures on the borehole wall are initiated at the perforation entrance holes and extend around the borehole wall.

The deformation and failure loads of the structure depend on the material properties and the structural properties such as perforation diameter and length. In general, the geometry of the individual perforations influences the stability less than the geometry of the structure, that is the shot density, shot phasing and pattern. A spiral pattern is the most stable with in- plane and in- line patterns becoming less stable respectively.

The shot density produced the most significant results. An increase in shot density reduced the stability and produced a disproportionately large increase in debris. The creation of debris is significant in that it may be mobilised and block the fracture surfaces.

The effect of local failure zones within the perforation will also affect the permeability of the failed and intact rock. Therefore, although the perforation fractures may be localised, they directly affect the fluid flow into the perforation and therefore the productivity.

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Table 1. Summary of results of physical modelling.

Parameter	Influence				
	Perforation stability	Perforation diameter deformation	Mode and orientation of fracture	Mass of debris produced	Debris size distribution (>500μ)
Perforation Length	1	1	X	2	2
Shot density	1	1	X	2	2
Phasing angle	2	2	X	1	1
Inline pattern	Weakest	Smallest	X	Highest	Highest
Inplane pattern	Medium	Medium	X	Medium	Medium
Spiral pattern	Stongest	Largest	X	Lowest	Lowest
Uncased borehole	Stronger	Smaller	X	Higher	Higher
Cased borehole	Weaker	Larger	X	Lower	Lower
Rock strength	2	X	X	1	Lower
Confining Pressure	2		X	2	Higher

1: Indicates that as the parameter increases the influence decreases

2: Indicates that as the parameter increases the influence increases

X: Indicates that the parameter has some influence

Table 2. Summary of results of numerical modelling.

Parameter	Influence		
	Distribution of stress and strain	Magnitude of stress and strain	Perforation stability
Boundary conditions	X	X	X
Model geometry	X	X	X
Element mesh	X	X	X
Element type	X	X	X
Rock properties		X	X
Perforation shape	X	X	X
Perforation length	X	2	1
Shot density	X	2	1
Inline pattern	X	X	Weakest
Inplane pattern	X	X	Medium
Spiral pattern	X	X	Strongest
Perforation diameter	X	2	1
Pressure differential	X	2	1

1: Indicates that as the parameter increases the influence decreases

2: Indicates that as the parameter increases the influence increases

X: Indicates that the parameter has some influence

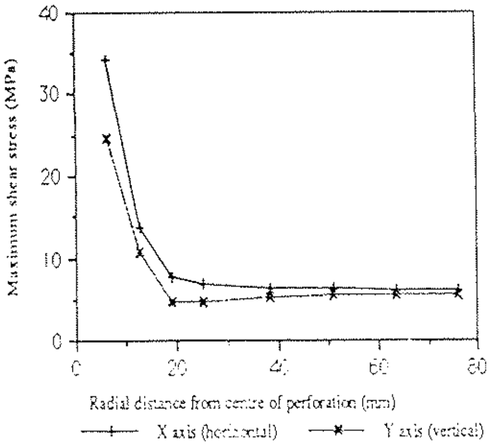


Figure 1. Max. shear stress in direction of X and Y axes.

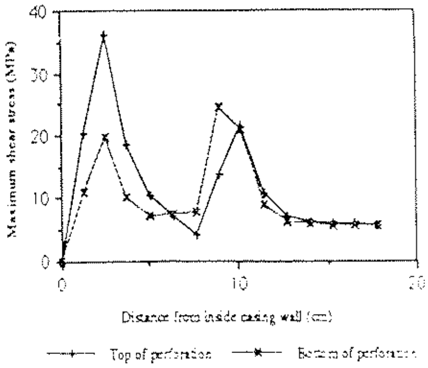
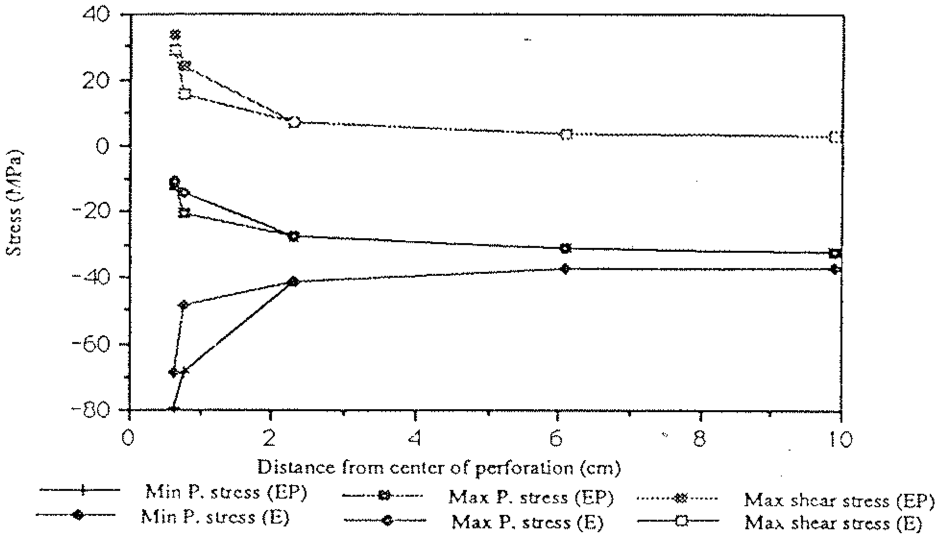


Figure 2. Maximum shear stress distribution along perforation



(E: elastic, EP: elasto-plastic)

Figure 3. Stress distribution around perforation in X direction (horizontal)

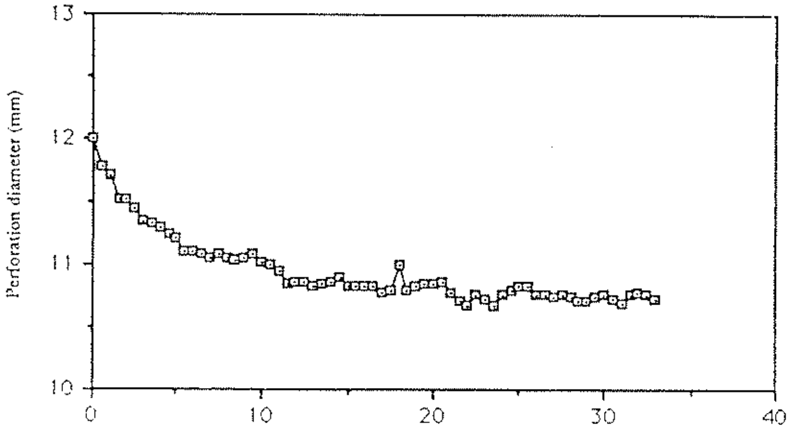


Figure 4. Perforation diameter reduction under applied vertical stress.

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