CATASTROPHIC FAILURE OF A RAISE BORING MACHINE DURING UNDERGROUND REAMING OPERATIONS

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Abstract—This paper describes the investigation of the catastrophic failure of a raise boring machine used for underground reaming operations. The results of the investigation indicate that failure was due to the fracture of the 32 drive head bolts, 30 of which had failed as a result of corrosion-induced fatigue. Metallurgical examination confirmed that the bolts had been manufactured in accordance with the SAE J429 Specification. A number of recommendations have since been implemented by the mine, who have also introduced a quality system specifically for the control of drive head bolt sets. The equipment has now operated without problems for several years. © 1997 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The process of raise boring (or back reaming) has been in use for over 30 years, and has proved to be a very successful technique in underground mining operations. Its primary use is in the production of interconnecting vertical or near vertical channels (raises) between underground levels in mines. However, this method of rock drilling can also be used for producing channels at any angle between the vertical and the horizontal [1].

This technique of underground drilling was developed to overcome some of the problems of personnel safety in the mining industry. Previously, the process of drilling and blasting was used, which required people to enter dangerous areas of mine workings. The development of raise boring techniques also gave the mining industry a new method to construct long ore passes and ventilation raises which is economical in both time and cost.

Current raise boring operations are used to produce raises of up to 6.0 m in diameter and up to 1000 m in length.

2. REAMING PRINCIPLES

2.1. *Rock mechanics*

The process of drilling and boring in rock differs from other similar engineering operations in two respects [2]. Firstly, the diameters and lengths of holes and tunnels in rock are usually much greater than those made in other materials, and the volume of material removed in making them is especially large. Secondly, the mechanical properties of rock differ significantly from those of other engineering materials. The latter usually deform in an elastic–plastic manner, whereas most rocks deform in an elastic–brittle manner. Rock is also a very abrasive material.

Typical stress–strain curves for an elastic–plastic material and an elastic–brittle rock are shown in Fig. 1. A consequence of the brittle or work-softening nature of rock deformation is that it tends to be unstable, and results in the formation of chips when a rock surface is loaded by an indentor of any kind. Virtually all mechanical devices for drilling or boring rock behave like indenters. However, the precise form of these working tools varies considerably in accordance with the strength, brittleness and hardness of the rock which they are designed to work. In general, they do not cut the rock in the usual sense of the word, but cause it to spall away on either side of the area
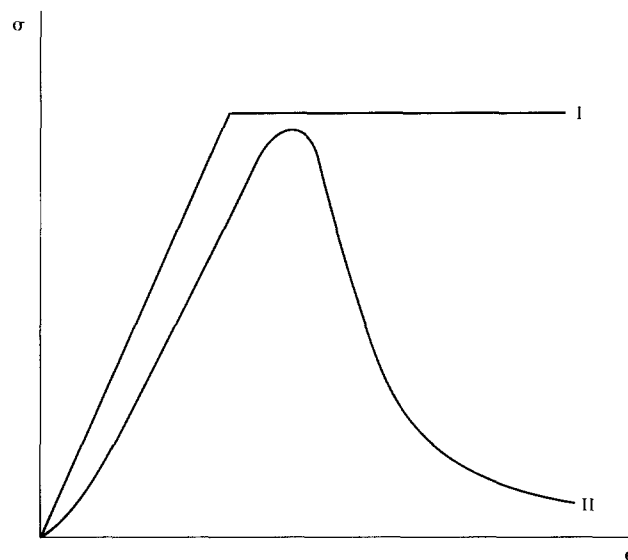
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Fig. 1. Stress–strain curves for an ideal elastic–plastic material (I) and an elastic–brittle rock (II).

of contact between the tool and the rock surface. Hence, the volume of rock removed by the passage of the tool is greater than the volume of rock penetrated. Penetration rates can be estimated from factors such as the specific boring energy, the power delivered to the working face, and the uniaxial compressive strength of the rock. The latter, however, is not an accurate guide to boreability, which can vary by a factor of 3 or more for rocks of similar compressive strength.

2.2. The reaming operation

The principle of underground raise production involves two basic operations: firstly, the drilling of a pilot hole, and, secondly, back reaming. A diagrammatic representation of a raise borer being used for the slope drilling of a pilot hole is shown in Fig. 2. During the pilot hole drilling cycle, drill rods connect the raise boring machine with a bottom-hole assembly consisting of ribbed stabilizers, roller reamer and pilot bit. The rock debris is flushed to the surface and collected in a settling drain. Any common flushing medium can be used, i.e. air, water or foam.

After the pilot hole has been completed, a raise boring head is used to back ream the required raise between the underground levels. The raise boring head has a number of rock cutters to facilitate the reaming operation (Fig. 3).

3. BACKGROUND

The catastrophic failure of the raise boring machine occurred during the reaming of a 3.66 m diameter by 266 m long hole at a dip angle of 88° to the horizontal (i.e. almost vertical). All 32 bolts on the raise borer drive head failed after 119 m of reaming had been completed. Prior to the failure, no abnormalities had been reported and the operation had been running smoothly.

The raise borer had been subjected to a major overhaul approximately 2 years before the failure. An exploded view of the drive head assembly, with respect to the derrick and base plate, is shown in Fig. 4. To facilitate the overhaul, the equipment was moved from its underground location to the surface. All the drive head bolts were replaced. A cutaway diagram of the drive head installation, showing the relative positions of the cover, drive head bolts and body, is shown in Fig. 5.

Since overhaul, the raise borer had been used to ream a series of smaller diameter (2.44 m) holes 92, 97, 89 and 91 m in length. The medium used for flushing was mains water. After these holes were reamed, the equipment stood underground for a period of 3 weeks. The next hole that was reamed was 97 m long, and was produced using mine service water for flushing. Catastrophic failure of the raise borer occurred during the reaming of the subsequent 3.66 m diameter by 266 m long
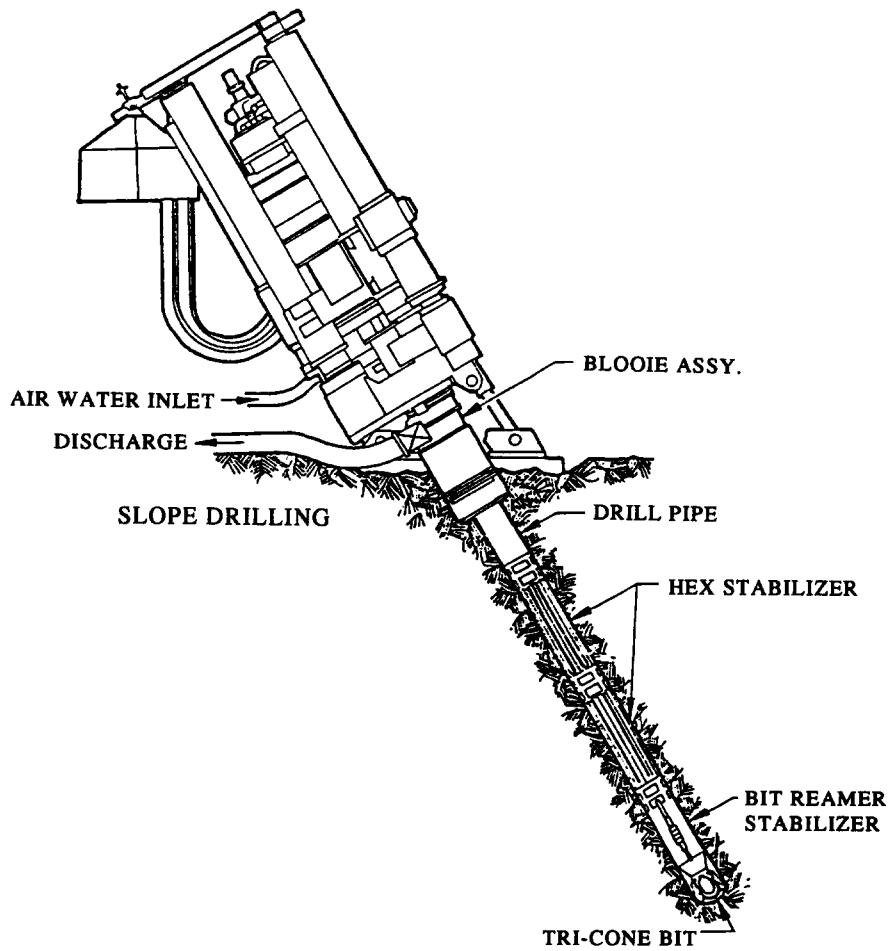
Fig. 2. Slope drilling of a pilot hole.
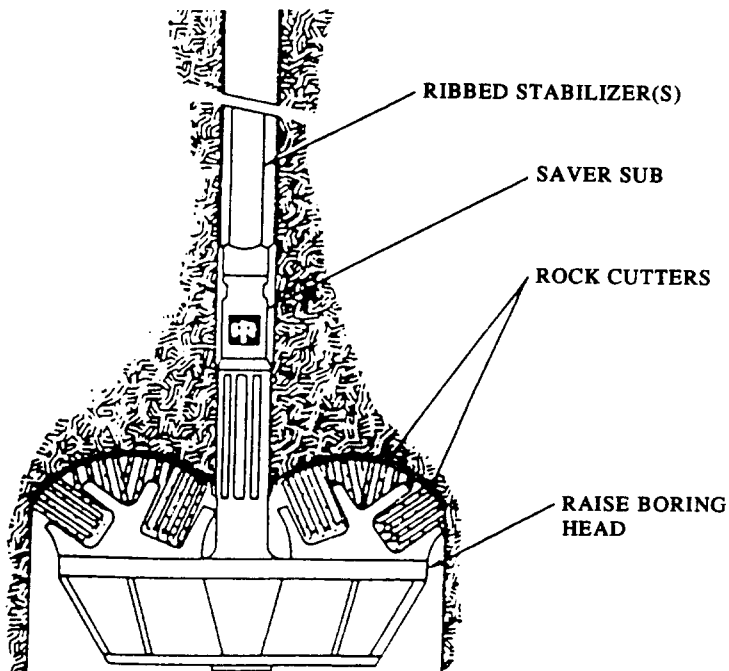
Fig. 3. Raise boring head and rock cutters.
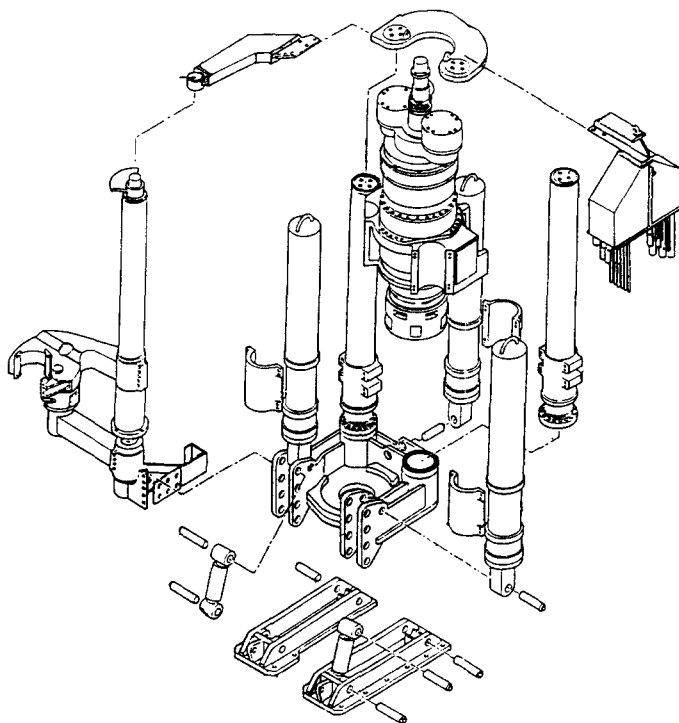
Fig. 4. Exploded view of the drive head assembly.

hole. The 119 m of rock had been reamed over a period of a few months at almost the full working capacity of the equipment. Mains water was used as the flushing medium.

The torque and thrust capabilities of the raise borer are as follows:

- maximum torque capacity: 494,876 N m (365,000 ft lb)
- maximum thrust capacity: 4454 kN (1,000,000 lb)

Fig. 5. Cutaway diagram of the drive head installation.

The applied torque and thrust during the reaming of the hole on which failure occurred was as follows:

- torque varied between 358,599 and 466,170 N m.
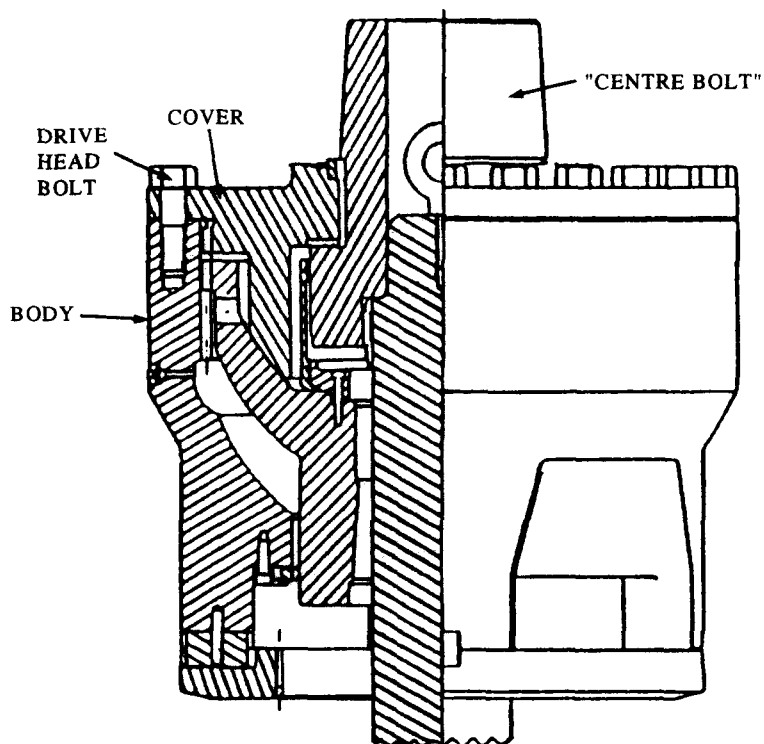- the original thrust was thought to be constant at approximately 4454 kN: however, on further checking it was found that the actual thrust was 5033 kN, i.e. 13% above maximum.

By design, the drive torque is transmitted through the connection via splines, and the drive head bolts are intended to carry only the applied thrust.

The bolts are 32 mm (1.25 in.) in diameter by 89 mm (3.50 in.) long SAE Grade 8 hexagonal head cap screws having a torque specification of 1140 N m (840 ft lb). Prior to installation, all the bolts are coated with an anti-seize compound.

4. SITE VISIT

A site visit was made in order to carry out an inspection of the raise boring machine, which had been brought to the surface and had been dismantled in the company workshops. During "breaking-out", it was noticed that the torque of the drive head cap screw or "centre bolt" was well below the normal figure.

The fractured bolt sections in the locating holes had been extracted and clearly identified in clockwise sequence from 1 to 32 (position 1 being at the 6 o'clock position for reference purposes). It was not possible to extract the sections of bolts 21, 25 and 28 due to seizure in the holes. The fractured bolt sections were subsequently "matched" to their corresponding bolt head sections by fracture surface comparison. The original orientation of each bolt in the locating holes had been marked on the bolt heads.

It was clear from the position of fracture of the bolt sections still situated in the body of the machine and the positions of fracture of the other bolts that failure had occurred at or near the joint between the cover and the body.

The underside surface of the cover, including the area containing the locating holes, showed general rusting from the ingress of water.

5. EXAMINATION OF THE FRACTURED BOLTS

The fractured bolts were visually examined on-site, and then examined in the laboratory using a binocular microscope after suitable cleaning. Apart from bolts 7 and 28, which had failed by 100% tensile overload, the failure of the drive head bolts was associated with fatigue. A view of the fracture surfaces of bolts 19 and 20, showing typical areas of fatigue, is shown in Fig. 6.

Each bolt was assessed in order to estimate the amount of fatigue crack propagation with respect to the cross-sectional area. The results are presented in Table 1.

In order to try and understand the nature of the stressing which had produced the fatigue cracking, the orientation of the fatigue crack origin(s) on each bolt, with respect to the original orientation of the bolts in the locating holes, was determined. A diagram showing a plan view of the positions of the fractured bolts and the corresponding fracture origins is shown in Fig. 7.

The general surface condition of the bolts was found to be poor, with extensive surface corrosion and pitting corrosion in the threads (Fig. 8).

6. METALLURGICAL EXAMINATION

6.1. *Chemical analysis*

Three bolts were arbitrarily chosen for chemical analysis, the results of which are presented in Table 2.

Fig. 6. Fracture surfaces of bolts 19 and 20, showing areas of fatigue from multiple origins (arrowed).

6.2. Scanning electron microscopy

The fracture surface of bolt 20, which showed a typical area of fatigue, was examined using scanning electron microscopy. At low magnification, the extent of the corrosion could be clearly observed, with the origins of fatigue crack initiation corresponding to corrosion pitting in the thread root. At high magnification, features typical of fatigue propagation were observed (Fig. 9).

6.3. Optical microscopy

Longitudinal sections were cut from bolts 3, 17 and 31, and prepared for optical microscopy using standard metallographic procedures.

In the unetched condition, the steel from which the bolts were manufactured was relatively free from non-metallic inclusions. Etching in 2% nital revealed a fine, tempered martensite micro-structure for each bolt, and no evidence of surface defects such as decarburization (Fig. 10).

Table 1. Area of fatigue crack growth relative to the cross-sectional area of each bolt

Bolt no.	Percentage area of fatigue	Bolt no.	Percentage area of fatigue
1	30	17	20
2	< 10	18	15
3	15	19	10
4	15	20	10
5	20	21	15
6	< 10	22	10–15
7	0	23	20
8	10	24	< 10
9	20	25	< 10
10	15	26	30
11	< 10	27	20
12	10	28	0
13	20	29	10
14	10	30	15
15	20	31	10
16	20	32	20

▼ MULTIPLE ORIGIN FATIGUE

▼ TENSILE OVERLOAD

Fig. 7. Plan view of the cover, showing the positions of the fractured bolts and the corresponding fracture origins.

6.4. *Hardness testing*

Hardness tests were carried out on bolts 3, 17 and 31 using a Vickers-type machine, giving an average figure of 385 HV. (The SAE J429 Specification for Grade 8 bolts has a core hardness requirement of 33–39 HRc, equivalent to 327–382 HV per ASTM A370). The hardness figures achieved on the bolts is equivalent to an ultimate tensile strength of ± 1230 MPa (ASTM A370).

7. DISCUSSION

The examination of the raise boring machine has established that 30 of the 32 drive head bolts have fractured as a result of fatigue cracking. The other two bolts have fractured in a purely tensile overload manner.

The fatigue cracking has originated from multiple positions in the thread roots, indicative of a high stress concentration and/or corrosion fatigue. Fatigue is characteristic of cyclic stressing, and the small ratio of fatigue area to final tensile overload area on the bolt fracture surfaces indicates a high operational stress. All the areas of fatigue on the bolts are associated with corrosion pitting.

Table 2. Chemical analysis of three bolts

Bolt no.	Mn	S	P	Si	Cr	Mo	Ni	Cu	Al	Fe
2	0.43	0.89	0.021	0.013	0.22	0.34	0.29	0.01	0.01	0.036 Balance
16	0.50	0.69	0.030	0.013	0.26	0.37	0.26	0.01	0.01	0.039 Balance
23	0.48	0.69	0.031	0.013	0.25	0.36	0.25	0.01	0.01	0.041 Balance
SAE* J429 Grade 8	0.28–0.55		<0.045	<0.040						Balance

Fig. 8. General surface condition of the bolt threads, showing evidence of pitting corrosion (arrowed).

The operating system of the raise borer must, therefore, be assessed in order to eliminate the high cyclic stressing and/or the corrosion.

It can be seen from Fig. 7, which indicates the orientation of the various fatigue crack origins relative to the original assembly position of the equipment, that there is no clear crack initiation pattern, and, therefore, no definitive pattern of cyclic stressing. However, the more-or-less random nature of the crack initiation is consistent with fracture by a corrosion fatigue mechanism. If the cover was "dishing" upwards during operation, this would have the effect of transmitting a high cyclic tensile stress on the inner region of the bolts, i.e. where cracking has originated on bolts 3, 4, 6, 8, 15, 16, 26 and 32. Similarly, for the downward "dishing" of the cover, the cyclic tensile stress would be greater where cracking has originated on bolts 12, 13, 18, 21 and 22. Clearly, the stress system in this case is complex. Measurements carried out on the cover indicated that the item was "dished-in" (downwards) by only 0.01 mm. The contact face of the body was also found to be perfectly flat so there was no apparent major permanent deformation of the cover or body.

The "centre-bolt" torque was found to be well below the normal figure during dismantling. This could have had the effect of allowing more vertical movement of the drive head cover. With the equipment working under such severe operating conditions it is essential that all cap screws and bolts are torqued correctly in order to minimise movement.

Based on the 552 mm² cross-sectional area of the drive head bolts (26.5 mm from thread root to thread root) and the approximate ultimate tensile strength of 1230 MPa, each bolt could theoretically withstand a tensile load of 679 kN before failure, and, therefore, the set of 32 bolts could withstand a load of 21,728 kN before failure. Considering a total thrust pressure of 5033 kN (the total thrust pressure includes the mass of the drill string) and the 32 bolts correctly assembled, the system is therefore operating at a factor of around 4.3. This will, however, be reduced due to the combined stress concentration effect of the thread root, and, more significantly, by the effect of corrosion pitting.

During assembly, the drive head bolts are liberally coated with a proprietary anti-seize compound,

Fig. 9. Scanning electron fractograph showing features characteristic of fatigue. × 3600.

which is described as a high-temperature, extreme-pressure, corrosion-resistant assembly lubricant. This was very difficult to remove prior to the laboratory examination, but, clearly, it does not afford protection to the surface of the bolts. Water seeping across the contact area (joint) of the cover and body to the drive head bolt locating holes can, therefore, penetrate the anti-seize compound.

A water additive is used for its lubricating and hole cleaning properties, but only if the system is a closed loop. In addition, the additive would have no corrosion-inhibiting effect on the water. A medium such as an oil-based red lead primer should be used at the connection joint between the cover and the body in order to prevent water from reaching the drive head bolts. The torque tightening of the 32 bolts will cause the compound to "spread" and allow satisfactory sealing of the mating surfaces.

Fig. 10. Longitudinal section of a bolt thread root showing fine tempered martensite, and no material or manufacturing defects. Etched in 2% nital. × 285.

The metallurgical examination of the bolts showed that the failure was not associated with any material or manufacturing defects. The bolts conformed to the specification requirements in all respects.

8. CONCLUSIONS

(1) The catastrophic failure of the raise boring machine is associated with the fracture of the 32 drive head bolts. Thirty of the bolts have failed as a result of corrosion-induced fatigue.
(2) The bolts have failed due to a combination of high cyclic stressing induced by the operation of the equipment at 13% above maximum thrust and corrosion from the water in the flushing system.
(3) Chemical analysis, microscopic examination, and hardness testing have established that the bolts conform to the required SAE J429 Specification.

9. RECOMMENDATIONS

(1) To prevent corrosion of the bolts the following measures are recommended:

    (a) An oil-based red lead primer should be used to create a barrier at the cover–body connection.
    (b) Mains water should be used at all times for flushing.
    (c) Equipment should not be stored underground for any length of time.

(2) Excessive thrust pressures during operation should be avoided, i.e. the equipment should be used within the limits for which it was designed.
(3) All components should be torqued to the correct figure to prevent excessive movement in the drive head.

10. FINAL NOTE

Since the investigation, a strict quality control system has been introduced at the mine for the control of bolt sets used on raise boring machines. In addition, all the report recommendations have been implemented, and the torque settings on the drive head bolts have been increased with the approval of the machine manufacturer. Following subsequent finite element modelling, the thickness of the cover and the length of the drive head bolts have been increased for greater stiffness. The equipment has now operated without problems for several years.

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