Comparing 360^{o} televising of drill hole walls with core logging

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ABSTRACT: This paper presents a method of investigation of rock masses, used as a complementary or alternative process to diamond core drilling. A first version of the equipment for filming was developed in Japan and presented on the occasion of the ISC '98 (Atlanta, USA, 1998), but its production was not continued. The present version, treated in this paper, was developed in France by René Colas (1998). It was introduced into Brazil in November 2001, and into Germany in 2003. In the first part of this paper the fundamentals of the method are presented. Improvements made during its use are used to highlight the gains in productivity when investigating rock masses by these methods. There follows information about the equipment used (hardware and software), and the method of reporting results. Thereafter, data, results and possibilities of application of the method are summarized and discussed, especially concerning the São Paulo Metro – Line 4, and the San Francisco River Water Transfer project, maybe, one of the first times in which the televising of percussion boreholes has been used on a large scale in the world. As a basis for analysis of the images obtained in these site characterization campaigns, an application of the Q-system classification of rock masses was made, for comparing conventional core logging with the televising of percussion-drilled borehole walls. We were therefore comparing disturbed (core) samples with the relatively undisturbed borehole walls, making possible the identification of some factors that influence the disturbance of recovered core samples. The comparative qualities of the same rock masses are presented in the last part of the paper, using the six Q-parameters.

1 GENERAL CONCEPT

The method reported here is applied to the televising of the walls of bore-holes with diameters equal to or larger than 75 mm, and up to 250 mm, comprising two principal phases: image acquisition and image processing. For the first phase an image acquisition module is used, that is a segmented tube that houses a series of devices. In the lower segment, with transparent walls, lamps and a conical mirror are included. In the upper segment, with steel walls, are located a digital camera, a magnetic orientation system and the hardware necessary for the transmission of the camera images to the computer on the surface. When operating, the module is suspended on a cable and inserted into the borehole, moving through the target section. Thus the cylindrical wall of the hole is illuminated at the same time that its images, reflected by the conical mirror, are aimed at the digital camera. Due to the action of the conical mirror, the images obtained and sent by the camera are annular, from which the second phase is performed in the computer, using software especially developed for the restitution of the cylindrical form of the walls, pictured as a developed surface or as a virtual core sample. Details of the equipment are presented in Sec. 4.

In a typical form of application, the televising *begins* in diamond-drilled boreholes, permitting the technicians to familiarise themselves with the images of the various domains of the mass and the recovered core. From then on, the method can be used on larger numbers of cheaper and much faster percussion borings.

2 PRINCIPAL ADVANTAGES

The method is notable for improving productivity in the performance of the site investigation, leading to a reduction in time and costs, and gives operational simplifications, as follows:

Table 1. Relative cost between methods

CORE DRILLING				
Description	Unit	Quant	USD/M	Total USD
Core drilling Ø 100mm	meter	100	150.00	15,000.00
			Total USD	15.000,00
TELEVISING, PERCUSSION AND CORE DRILLING				
Activity option	Unit	Quant	USD/M	Total USD
Core drilling Ø 100mm	meter	40	150.00	6,000.00
Percussive drilling	meter	60	50.00	3,000.00
Televising services	meter	100	40.00	4,000.00
			Total USD	13.000,00

2.1 *Productivity improvements*

This is the result from the mobility of the equipment (mobile unit) and of the option to perform the televising in percussion holes, on a large scale. With the accesses prepared and depending on the distances between holes, the average daily production of a rotary-percussion borer, in the boring of holes 100 mm in diameter, is in the range of 60 to 100 meters. To the extent that they are readied, the holes can be televised at the rate of 60 meters per day per crew. The combination of percussive boring and televising covers 6 to 10 times more linear meters of hole per unit time, than diamond core drilling.

2.2 Reduction of time and cost

Greater productivity leads to reduction of the time schedule and the cost of the geotechnical investigation campaign. In the execution of 100 meters of rock boring with a diameter of 100 mm, the combination of percussive drilling and televising reduces the direct prices to about 86% of the price of diamond core drilling (Table 1). Bigger cost reduction are seen with more percussion holes.

2.3 Ease of visualisation and description of rock mass

Experience in Brazil demonstrates that televising reveals the rock mass close to its natural condition of occurrence, permitting the recognition of colour, granulation, texture, jointing and filled discontinuities. In general, the images indicate that the conditions of the mass are not as *unfavourable* as the core samples alone might suggest. This will be shown later on, in relation to the application of the Q-system for describing rock mass parameters. Among the improvements in visualisation and description of the mass are found the following:

2.3.1 Precise positioning of discontinuities in the mass

As the walls of the hole are pictured with a coverage of 100%, and thanks to the depth counter that registers the position of the sections pictured, the images locate the discontinuities in the mass exactly, while in core drilling the segments that compose the sample are not always completely recovered, thereby introducing inaccuracies in the evaluation (details below).

2.3.2 Automatic computing of discontinuities

In the images of the walls of the holes, formed as a developed cylindrical surface, the traces of dipping discontinuities appear as sinusoidal waves. The system software automatically computes the corresponding geological strike and dip angle, through the marking of three points in each trace, an operation performed by locating the cursor and clicking the mouse at each point. Linked to other computer applications, the system software provides a representation of the discontinuities in rose diagrams or lower hemisphere polar projections, or 'pap-logs' of dip and strike.

2.4 Ease of storage of bore profiles

With the elimination of most of the core samples of the rock mass, the televised profiles are filed electronically. A single CD, with 800 Mb memory, stores images equivalent to 500 meters of drilling. In core drilling, the boxes of samples must be preserved for a certain time, occupying physical space, and re-examination of samples implies visits to the storage location, manipulation of the boxes and correction of the profiles, requiring greater time in comparison with the time spent in re-examination of image profiles. If televising is used to complement drilling, photos of the real samples may be located with the virtual samples along the televised profile, permitting comparisons of the positioning and origin of discontinuities of the mass, either natural or induced, or those actually destroyed during drilling and core recovery.

2.5 Preparation of the report of results

In addition to the traditional printed format, the report of results of the televising of the bore-hole walls is furnished recorded on CD(s) that cannot be edited but permit viewing the entire profile of the hole (image of the hole wall surface and of the "core" sample), accompanied by the "pap-log" graph indicating the angle of strike and dip of the discontinuities along the profile, with a legend of the respective classes (joints with and without fill, etc.). Polar projections and rose diagrams are options to be combined with the body of the report (see details of the software below in Item 4.2).

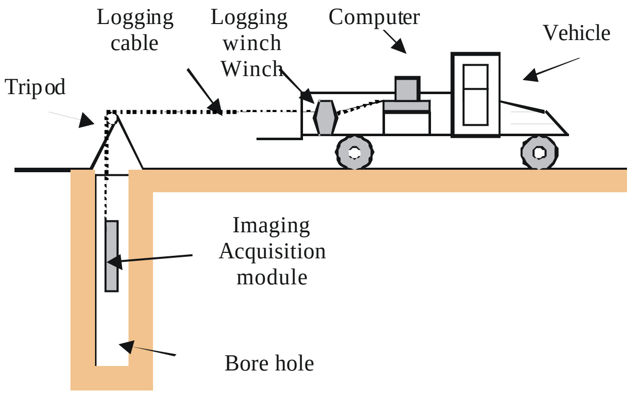


Figure 1. The basic equipment

3 EQUIPMENT DETAILS

3.1 Hardware

The equipment used in the televising method is mounted and transported on a rubber-tyre vehicle, comprising a series of units (Figure 1).

3.1.1 Image acquisition module

This consists of a segmented tube (Ø=60mm) (see next, Figure 2); that is introduced into the borehole (minimum diameter 75mm) and connected to the computer installed on the surface near the hole. It houses several devices, particularly *lamps* to illuminate the wall of the bore-hole, a *conical mirror* to reflect and direct the wall images, a *digital video camera* to capture the images, and an *orientation system* so that the images will be referenced to the cardinal points. The focal distance of the camera may be adjusted. A conical device made of high-resistance plastic is connected to the lower end of the module to protect the apparatus from direct shocks in case of obstruction in the bore-hole. The upper cover of the module is provided with a central hole for passage of the support cable (see following item).

Figure 2. Imaging acquisition module

3.1.2 Module suspension and displacement system

This system consists of a *logging cable* Schlumberger 92.264 4.18P, linked to the interior of the *image acquisition module;* the cable, controlled by a *logging winch* on the surface, also provides electric energy to the module and electronic transmission of the data collected. Provided with a *depth counter*, the system monitors the position of the module in the bore-hole in real time.

3.1.3 Computers

To acquire and process the images, the computer must have a RAM memory of 512 Mb, a HD of 40 Gb, an AGP video board with 64 Mb and a CD recorder. In addition, the image acquisition computer must be equipped with an additional mobile HD, CPI board specifically for the depth counter. For simple visualisation of the images, without editing, the computer must be provided with a Windows NT or XP (NTSF) system, a RAM memory of 128 Mb, and a drive for the CD-ROM.

3.2 Software

The annular and oriented images sent by the module are processed by the software, providing a quite ample view of the profile of the rock mass along the bore-hole, with control of the depth in each section. The final images can therefore be formatted as a developed cylindrical surface or as the virtual equivalent of a 'core sample' that is seen to rotate, or is held still, as the user requires. During the entire process, the computer works with three programmes, as follows

3.2.1 Maki Cam

The acquisition programme for the bore-hole wall image is actuated by a computer with characteristics described above. The image acquisition programme makes images of the wall about 30 cm long, through an optical arrangement consisting of a group of 12 lamps reflecting on the surface of a truncated cone of polished aluminium, which illuminates the wall, the image of which is reflected by a conical mirror and captured by a camera housed in the interior of the module. Each image of 30 cm or 624 pixels in length, is composed of 156 slices of the image, taken at a speed of about 0.5 m/minute, with its depth and orientation registered.

3.2.2 Maki Cad

This is the image processing programme, which integrates the slices along the entire profile of the hole, composing a single image, including correction of possible distortions. The rose diagrams, stereograms and profiles of the 'pap-log' type, are produced automatically, at the termination of the plot of joints and filled fractures, being discrete according to the classification chosen for the discontinuities by the user.

3.2.3 MakiVision

A unique vision programme, especially created for the user to take advantage of all its resources with efficiency, without the necessity of a learning period, providing the opportunity to translate the images at various speeds and the reconstruction of "virtual samples" and their animation. The software is intended for the visualisation and analysis of the Image Profiles, Sinusoidal Profiles of the discontinuities and their Profiles, as well as the polar profile of the strike and dip of each of the discontinuities, and their Rose and Stereograph Projections, with an option for printing them. Each file sent to the client is accompanied by instructions on operation of the software, the simplicity of which assures its complete operation without any prior training, and in any type of computer, fixed or portable, that has a memory greater than 126 Mb.

4 BRIEF NOTES ON PROJECTS IN WHICH TELEVISING IS BEING USED MORE INTENSIVELY IN BRAZIL

The present work is based on televised data collected in the investigation of rock masses in projects of great importance, which will be constructed, now in development in Brazil. To these have been added others collected in experimental holes, as described below:

4.1 São Paulo Metro – Line 4

In the São Paulo Metro transport network, the pioneer 20,2 km North-South line; the 22,0 km East-West line, integrated with the commuter rail lines; and the 7,0 km Paulista Branch, linked to the North-South Line, have already been implemented. In sum, the existing system has capacity to transport 5,4 million passengers per day, but the population is 17 million. Now, work is beginning on the 6,7 km Line 4, linking the Centre to the Western Zone of the city. In general, Line 4 will be developed in tunnels, which may be excavated using either a Shield and TBM, or the NATM method, depending upon subsurface conditions.

4.2 São Francisco River Water Transfer System

By means of a partial diversion of the flow (average about 2.060 m^3/s) of the São Francisco River, the project proposes to irrigate arid areas in the

Table 2. Site investigation résume

São Francisco river water transfer system			
Site investigation	bore holes	length(m)	length %
Core drilling	17	447.66	31.6
Core drilling with televising	5	95.30	6.8
Percussive drilling and televising	48	874.00	61.6
Total	70	1,416.96	100.0

Northeast of Brazil. To cross the mountain ranges between the contributory and beneficiary basins, as well as the use of natural stream beds, a series of channels, tunnels and pumping stations have been designed, involving excavation of rock and soil. The operational optimisation of the system will be achieved through implementation of reservoirs in the beneficiary basins and installation of hydroelectric power plants, with partial recuperation of the energy to be expended in pumping. The rock masses involved in the future construction of the project were investigated by means of televising core drilled holes and larger numbers of percussion drilled holes.

4.3 Experimental bore-holes

In addition to the cases in which televising was used in development of large projects, in others the method was employed in isolated holes, or in an experimental manner. In the initial situation, there was the necessity of complementing the data from core drilling, in gapped sedimentary rock, proposed for location of a dam on sandstone (the Furnas Formation). During the core drilling, to a depth of 15 meters, no recuperation of solid material was made, but its walls could be televised. In another case, a rotary boring was made in granite in the Barueri region, exclusively for tests of televising the walls in a section of rock at depths between 17 and 43 meters (or more precisely 17.46 and 42.60 m).

5 Q-SYSTEM FOR DESCRIPTION OF ROCK MASSES AND 360^O TELEVISING OF HOLES

5.1 Evaluation criteria for rock masses

The proposed format for recording the statistical variation of the six Q-parameters has recently been described by Barton, 2002. A sheet contains six main areas for recording the frequency of observations of the six Q-parameters, which are combined in the following way to calculate Q:

$$Q ? \frac{RQD}{Jn} x \frac{Jr}{Ja} x \frac{Jw}{SRF}$$

(Note: Q=0.1-1= very poor, 1-4 poor, 4-10 fair, 10-40 good etc.)

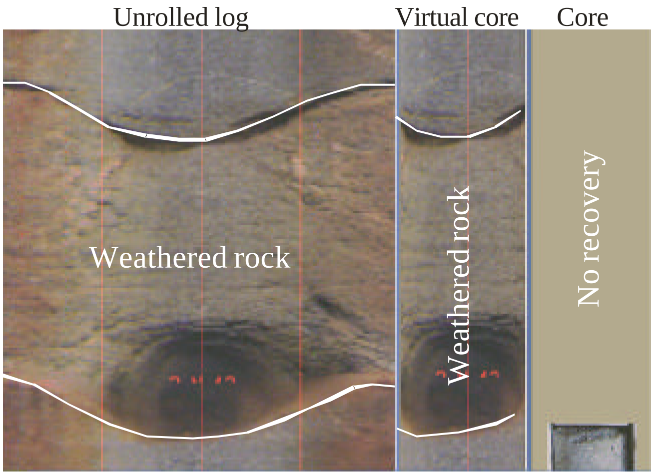


Figure 3. Weathered rock image

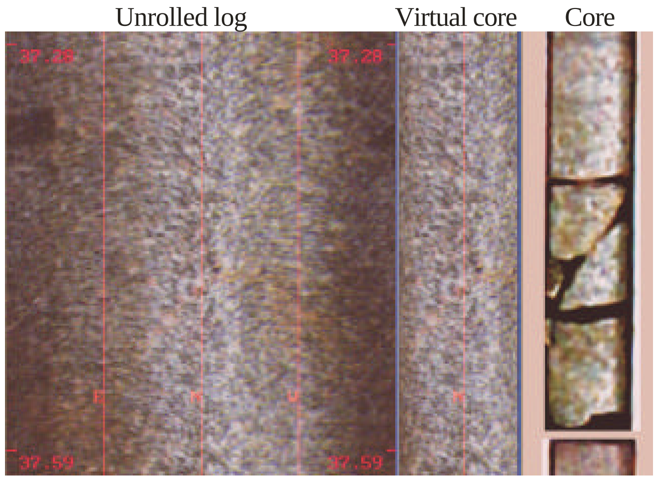


Figure 4. Incipient fractures image

The definitions of these six parameters is shown to the right-hand-side of each histogram, and the relevant descriptions and ratings are given above and below each histogram. Hand-written recording is followed by EXCEL plotting and calculation.

5.2 Some typical conditions of masses observable by televising

In recent rock mass investigative campaigns in Brazil, virtual and real samples were compared, indicating the utility of televised images in complementing data from rotary borings, revealing certain features of the mass, such as alteration and fracturing of the rock, as follows:

5.2.1 Tension of weathered rock

Along the televised profile, the extension of altered rock can be seen, generally as a function of the colours and reduced brightness that appear. Figure 3 shows images from the survey of the rock to be crossed by Line 4 of the São Paulo Metro.

5.2.2 Incipient fractures

In the case of core drilling in rock masses with incipient fractures, the forces and vibrations of the drilling induce an increased development and frequency of fractures in the samples, producing low RQD indices, possibly leading to underestimates of the quality or support capacity of the mass. The televised images presented in Figure 4, show a granitic rock mass from the Barueri region, São Paulo State, with closed or poorly developed joints, the recognition of which required a careful and detailed examination of the developed cylindrical surface. The televising, proving the incipient character of the joints, and showing that their development is too small to cut through the virtual sample, suggests that some increase could be applied to the rock quality index, above that which examination of the real core sample would lead one to apply.

5.2.3 Voids and erodible filling materials

These occurrences produce low recovery from cored samples. As a consequence, the juxtaposition of segments that compose the sample does not help to determine the exact positioning of the discontinuities. Boring equipment with hydraulic jet does not correctly sample filled discontinuities of this type and, in consequence, in the core box, the filled discontinuities are not correctly represented. (With old borings, from mechanical drills operated manually, a well-trained surveyor could detect such an occurrence, and place a wooden spacer.) In televised images, the discontinuities appear in their natural positions, making possible the determination of the individual thicknesses of the filled discontinuities, of the layers of materials, or the dimensions of the voids. Figure 5 refers to the detection of a horizontal fracture, with a 6 cm opening in the mass, partially filled with rock fragments. In the example, it can be verified that the juxtaposition of the segments of the real sample does not permit the definition of the position of the fracture with any assurance. RQD estimates are therefore changed.

5.2.4 Vertical fractures flanked by incoherent materials

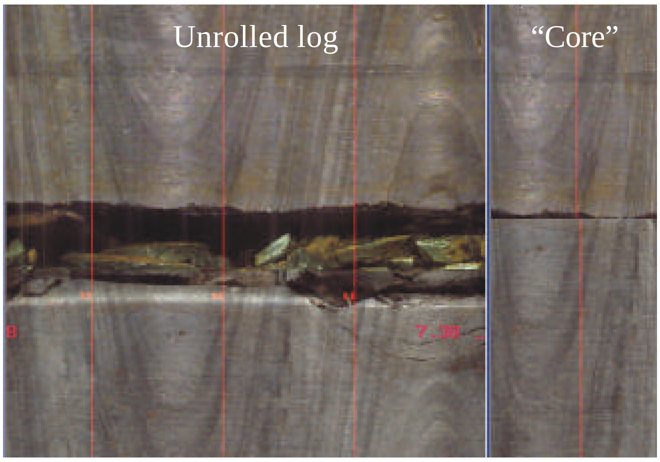


Figure 5. Voids and washable material image

This situation is pictured in Figure 6, in which the disturbance of the boring itself lead to washing of the incoherent materials (strongly weathered rock along one side of the vertical fracture) and intense fragmentation of the remaining rock, in spite of the greater coherence of this material. In this case the samples found in the core box are nothing more than an agglomeration of disconnected fragments, with a zero RQD index, it not even being feasible to conjecture the percentage recovery of the real sample. The televised data remain the only resource available for an evaluation of this particular rock mass location.

5.3 Q-index of some masses studied in the design of São Paulo Metro

For the study of the rock mass quality index, both by the examination of real samples and televised images, the profiles of rock mass borings were surveyed, in the course of the geotechnical investigation campaign for the final design of São Paulo Metro – Line 4. The criteria of selection were: 1) the study of diverse masses, not only in lithological terms but also as to the degree of alteration and fragmentation of the rock; 2) make

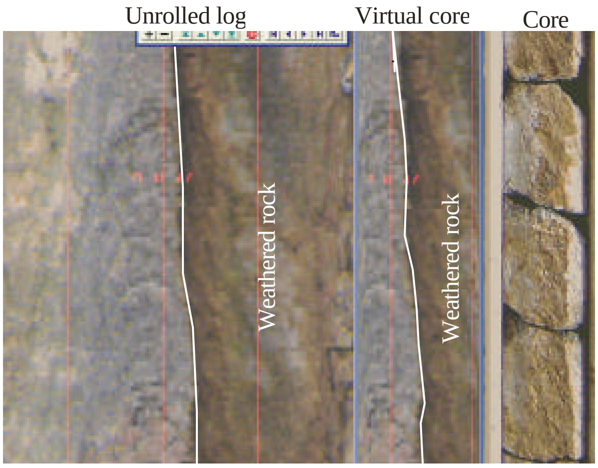


Figure 6 Voids and erodable material image

possible the checking of the classification of the mass by different consultants who worked in the project development and/or the implementation of the works.

In accordance with these criteria, eight domains of rock were selected, crossed by borings SM-04 and SM-11 in the investigative campaign, of which the holes were also televised. At each domain possible, variations of basic parameters and respective quotients that define the rock mass quality index were evaluated, based on the examination of real samples and the analysis of images.

The variations having been identified, the results reflect the best and the worst values that can be indicated for the quality of the various domains of mass analysed. In the case of the televising, the lengths of the segments that compose the virtual samples, separated by visible fractures in the mass in its natural state, were verified, for assignment of equivalent RQD indices. The selected domains and the tabulation of results referring to the evaluation of the mass quality indices are presented in condensed form in Figure 7.

6 DISCUSSION AND CONCLUSIONS

Examination of results in the previous procedure confirms the expected tendency that, using televised images, higher quality classes may be assigned to rock masses, as compared with an evaluation based on diamond cored samples. To show better this result, the Q-index variation found for the eight domains of rock were located on Q-system classification scale (Barton, 2002) as indicated in Figure 7, in correspondence to the best and worst conditions of the mass in each domain studied. Figure 8 represents an exemple of the Q-parameter histogram method of logging (Barton,2002) with a conceptual image of likely bi-modal distribuition of RQD, J_n and J_a, that is expected to be obtained if television wall logging and core logging were combined on one sheet. In general, the results lead to the following discussion and conclusion:

6.1 Variation of the RQD/J_n Quotient

This quotient, where denominator represents the number of joint families, shows the tendency to assign to rock mass classifications relatively higher values by the televising method. If the best condition is considered, the quotient evaluated by televising is two or three time greater than that obtained by core logging. If, on the other hand, the worst condition is considered, the tendency is accentuated, with the quotient based on televising becoming three to six times greater than the other. This result is also reflected in the relative positioning of the classifications indicated in Figure 7. The reason for this is evident in the conception and application of the televising method, in that the images obtained, with an *index of wall recovery* of 100%, picture the mass at the periphery of the boring, the zone least subject to damage induced by mechanical boring, and therefore in a condition much closer to natural. The segments of the video wall sample tend to be separated only by natural fractures, the incidence of segments with a length of less than 10 cm being quite rare, leading to RQD wall parameters greater than those produced by rotary borings.

SÃO PAULO METRO: GEOMECHANICAL CLASSIFICATION OF ROCK MASSES

Bore-Hole nº.	Depth m	Domain nº/ litology	Rock Mass Classes Related to Q Value							
			Ext.poor	Very poor	Poor	Fair	Good	Very good	Ext. good	Exc. good
			0,01 0,1	1	4	10	40	100	400	1000
SM L4 04	35,90	1		0,17 - 0,3						
	37,30	milonite					11,0			
		2				7,5 - 22,5				
	38,76	q. vein					16,5			
		3		0,2		4,9				
	40,15	milonite					11 - 16,5			
SM L4 11	19,35	1				7,5	11,2			
	22,00	gnaiss				7,4	16,5			
		2		0,4		4,5				
	28,20	gnaiss				7,4	33,0			
		3		0,4	3,8					
	33,82	migmatite				7,4	33,0			
		4	0,0			8,7				
	38,20	schist					11,2	50,0		
		5		0,4			16,5			
	53,24	migmatite				4,9	33,0			

CORE

TELEVIEWER

Figure 7. Comparison of core drilling and televiewer logging

Another reason for this result is the variation of the *J*n parameter, the number of families of joints in the mass. At times, the evaluation of this parameter coincides in both the methods, while televising rarely indicates a lower value. However, the fragmentation of boring samples, greater than that of televised wall samples, results in worse values for this parameter, combining to reduce the quotient RQD/Jn. In this respect, it is important to also consider that in the televising method, the measured joint traces are easily transferred to a polar diagram in which the families are easily recognised.

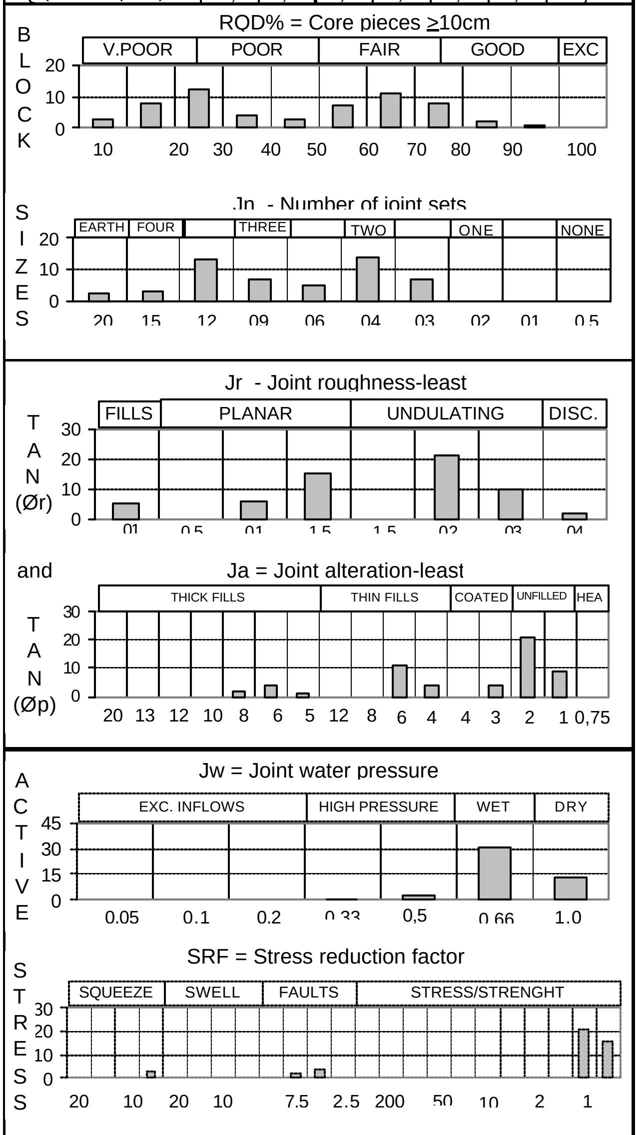
6.2 J_r / J_a Quotient

In masses of sound rock, with high RQD indices, the examination of boring samples permit a very realistic evaluation of the Jr parameter, referring to the roughness of fractures. In the opposite case, with low RQD indices, the evaluation of this parameter is somewhat impeded due to the creation of fractures by the boring and to the reworking of the pieces themselves that make up the samples, disfiguring the natural characteristics of the surface of the joints. When the joints or discontinuities are open, not filled, a view of their walls can also be had by televising. On the other hand, so as not to harm the evaluation of the parameter Ja, referring to the alteration of the mass along the fractures, it is indispensable that careful attention be paid to the images of the first cored holes. A tendency to over-evaluate this parameter may occur in televising, in rarer cases in which the images do not permit distinguishing altered or filled material from the rest of the mass. With all these possible tendencies, some of them prejudicial, the results of the quotient Jr / Ja may tend to one or the other side, and not indicate a consistent tendency for this or that method. The correct evaluation of the parameter Ja results from good technique in both methods being compared, with regard to recovery of core samples, and gauging borehole wall images in cored holes.

6.3 J_w / SRF Quotient

The parameters that define this quotient are difficult to evaluate, either by the conventional method of investigation of rock masses, with examination of boring samples, or by televising. The denominator of the quotient SRF, Stress Reduction Factor, that pictures the state of stress in the mass, is a parameter generally evaluated as a function of more ample knowledge of the mass, including considerations of prior experience in excavations, or results of tests in situ, in short, independently of isolated data obtained by core drilling or by televising. In the case in point, the rock mass in the São Paulo Metro – Line 4, the SRF parameter is evaluated as 1.0. The parameter Jw, in turn, refers to the value of water flows through the joints, which, in whatever hypothesis, always should be checked with especial attention during and after excavation. Divergences may arise in the evaluation of this parameter, to the extent that the televising reveals materials or fill in the fractures, reducing possible flow, at the same time that these materials are washed out in the process of core drilling, possibly increasing flow. Thus, in the specific case of the rock masses analysed in the present work, in the examination samples this parameter was assigned class C: high value flows or under high pressure along joints without fill, with a value equal to 0.5, while in televising the same parameter was assigned to class B: medium value flows or under medium pressure along the joints, with occasional out-washing of fill material. However, the experience acquired in excavations of the rock mass, may recommend an alteration of both evaluations.

Q-VALUES:	RQD	Jn	Jr	Ja	Jw	SRF	Q (*)
Q (typical min)=	7,0	20,0	1,0	8,0	0,3	7,5	**0,002**
Q (typical max)=	95,0	3,0	4,0	1,0	1,0	1,0	**126,7**
Q (mean value)=	46,0	8,1	1,9	3,4	0,7	2,2	**1,05**
Q (most frequent)=	25,0	4,0	2,0	2,0	0,7	1,0	**4,13**



COMPARISON OF CORE LOGGING AND TELEVIEWER LOGGING

Three of the Q-parameters show significant divergence (RQD, Jn and Ja) due to minimized disturbance when televiewing the wall, instead of retrieving and handling core.

$$*Q = \left(\frac{RQD}{J_n}\right)\left(\frac{J_r}{J_a}\right)\left(\frac{j_w}{SRF}\right)$$

Figure 8. Q-parameter histogram

6.4 *Final Considerations*

In the example shown in the spread-sheet (see Figure 8) we have imagined the combined result of conventional core logging using this system, together with the likely result of 360° borehole televiewer logging. For purposes of emphasis, we have shown how the recording of three of the parameters may be quite different, due to the better preservation of sensitive features in the borehole wall, as compared to the disturbed (or partly washed away) feature in the core. The bi-modal distributions of RQD, J_n and J_a show where the chief differences are likely to occur, due to reasons that will have become obvious, when studying the visual images of core-and-wall comparisons.

The advantage of recording observations in Q-system format is that many empirical links to rock mass parameters have been developed, for example deformation modulus and measures of rock mass strength, including the cohesive and frictional components of the rock mass – i.e. those requiring shotcrete and rock bolt support in the context of tunnelling. Q also correlates closely with the seismic velocity, making cross-checking (and extrapolation) between televiewer logging and remote sensing possible. Intuitively, the correlation between any televiewer logging of Q and velocity, should be more reliable than the correlation of any core logging of Q and velocity, due to the reduced disturbance. However the empirical correlation might change as a result.

The graph of Figure 7 shows, in general, that the most unfavourable classification of the mass, found by analysis of televised images, is situated in a category equal to, or immediately higher than the most favourable classification assigned to the same rock mass based on examination of core samples.

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