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East Tunnel

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2.4 Probability of boulders

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Introduction

To collect background information for formulating a description of the expected soil properties along the tunnel line, in 1987 Storebælt initiated a statistical investigation of the occurrence and size of boulders on the cliff beaches in the Great Belt area. The data collection part of the investigation was made on the basis of geological expert advice (Professor Gunnar Larsen, Århus) by the Danish Geotechnical Institute (DGI), while the author, Professor Ove Ditlevsen, was in charge of detailed statistical analysis of the data.

Data collection and analysis

The data were obtained by aerial photography of cliff beaches, with subsequent stereometric measurement on the photographs. The areas of observation were defined as reaching from the toe line of the scree at the foot of the cliff to lines parallel to the water line at 0m, 2m, or 4m out in the sea. A typical beach cliff is shown in Figure 2.4-1. The position as well as the main dimensions of each single boulder were recorded.

▲ *Fig. 2.4-1 Typical beach with boulders*

Analysis revealed a remarkably simple relative size distribution of the boulders. The main dimensions of each boulder were measured by idealising its shape as an orthogonal box. Thus a largest dimension, a smallest dimension, and an interjacent dimension were defined. In total 800 boulders with their largest dimension exceeding 550mm were observed.

It transpired that the number of boulders whose largest dimension exceeded an arbitrary amount decreased by 0.1 for each increase of this amount by 500mm, ie the distribution was exponential. Moreover, it was found that the ratio between the smallest and the interjacent dimensions was distributed between 0 and 1 exactly as the ratio between the interjacent and the largest dimensions was distributed between 0 and 1. The average of both ratios was 0.71 and the common distribution was well matched by a beta distribution (density proportional to $x^{5.36}(1-x)^{1.57}$ for $0<x<1$). Finally it was found that the largest dimension and the two side ratios were distributed statistically independent of each other. This meant that a randomly chosen boulder would have main dimensions as if they were determined by independant and random choise of the three mentioned quantities from each of the three distribution, respectively.

The usefulness of this information with regard to specifying reference conditions for the tunnel drilling naturally depended on whether the unknown distribution of boulder sizes along the tunnel line was the same as that found along the cliff beaches. However, a further observation supported this conclusion: the size distribution could not be shown as significantly different at seven beach localities at which 800 free boulders were examined, even though these localities are widely separated over the entire Great Belt region. On the other hand, the density with which the boulders were estimated to be deposited in the till at the different localities varied very widely. This was gauged by referring to a till volume per unit length of the shore line, defined as the product of the local width orthogonal to the shore line of the area being examined, and the local cliff height. Naturally there is in general a greater density at promontories than on straighter beaches.

Since the purpose of the investigation was to get information not just about the size distribution but also about the density along the tunnel line, the DGI also made a series of seismic measurements, from a ship travelling up and down the tunnel line along 40 parallel straight lines within a 420m wide and 2500m long scanning corridor. Small paraboloid curves on the seismogram could, with some reservations, be interpreted as defining the positions below the seabed of boulders with vertical dimensions >500mm – one quarter of the wavelength of the sonar signal.

Assuming that the boulders were homogeneously distributed over the scanning corridor, a maximum likelihood calculation led to an estimate of the density of missing or undetected boulder signals. Thus a statistical correction for any observational inconsistency was obtained.

However, individual boulder sizes are not measured by seismic registration, so the size analysis method used in the beach boulder investigation had to be employed to relate the density of observed boulder positions to the density of boulders with a maximum dimension larger than any given figure. This calculation required the extra assumption that the boulders were fixed in the till with their smallest dimension approximately vertical.

A hypothesis that the diffracted signal from a boulder is detected only if the returning sound wave exceeds a certain threshold was handled by use of a classical first order model of sound wave diffraction derived by Rayleigh. This model predicts that the far field sound pressure is proportional to the volume of the boulder and inversely proportional to the distance from the centre of the boulder. The statistically supported view that the boulder position point field was statistically homogeneous along each line the ship travelled and over the entire depth of the till deposit was used – with Rayleigh's diffraction model – to determine the top angle of a vertical circular cone with its vertex at the sound source. It was assumed that only boulders situated inside this cone could be detected and, further, that the received wave pressure was independent of the angle with the vertical of the incoming wave.

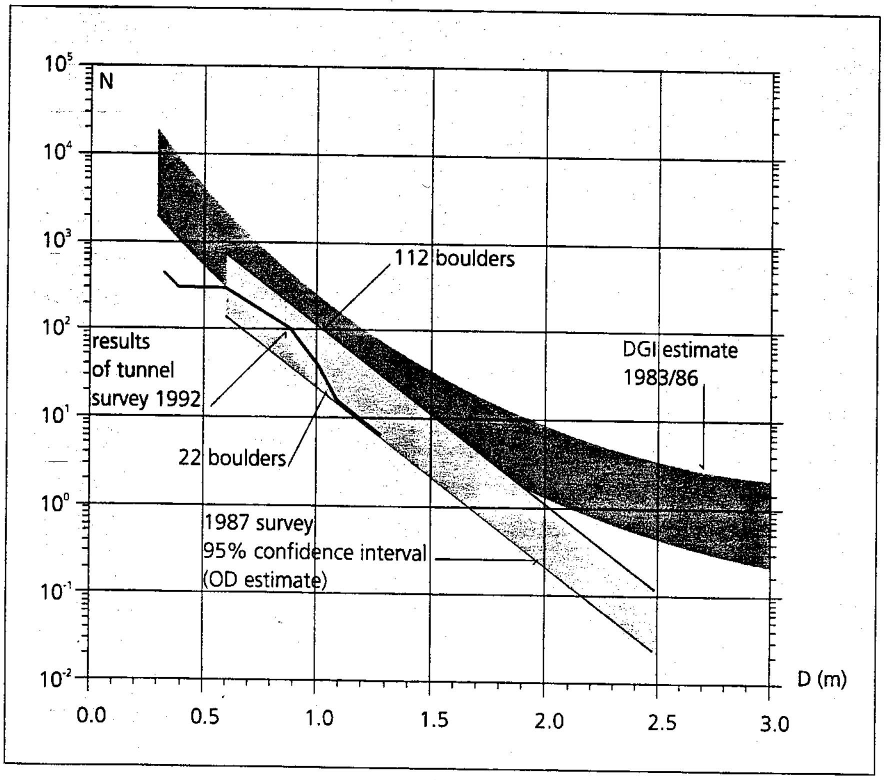
This model set-up made it possible to calculate with reasonable certainty that the cone angle was about 35°. Obviously this cone defined the reference volume of till along the ship-traversal lines.

On the basis of these considerations, for which the statistical homogeneity hypothesis is crucial, it is possible to estimate confidence intervals for the expected number of boulders whose largest dimension exceeds, say, 1m per volume unit of till along the tunnel line. While bearing in mind the uncertainties of the seismic measuring method, including its interpretation, the estimate it gave of the expected number showed a linear variation from c35–53 boulders of largest dimension exceeding 1m per 100 000m³ of till across the seismic scanning corridor from the south to the north boundaries. Figure. 2.4-2 shows the estimate of the 95% confidence interval for the number of boulders along the north boundary of the scanning corridor. For the maximum dimension larger than 1m the interval ranges from 22 to 112 boulders.

Tunnel construction

This result of the evaluation of boulders was summarised by Storebælt in the contractual reference condition as the basis for the design of the TBM cutter heads and detritus transportation systems. It was further recognised in the specification that ground treatment could be required for the removal of boulders from the cutter heads.

Contractor and client representatives systematically recorded the boulders from the first 61 500m³ of tunnel excavation in the upper till. As shown in Figure 2.4-2, it was found that the number was well within of the estimated 95% confidence interval from the 1987 survey, allowing for missed counts.



◀ *Fig. 2.4-2 Pre-tender assessment of expected number N of boulders with maximal size larger than D per 100 000 m³ of till and of direct measurements made during the tunnel excavation in 1992 of the first 61 500 m³ of till.*