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PROSPECTS FOR STEREOLOGY IN CIVIL ENGINEERING

Piet Stroeven

Stevin Laboratory, Delft University of Technology

Stevinweg 4, 2628 CN Delft, The Netherlands

ABSTRACT

So far stereological techniques have not widely been used in civil engineering. Fertilizing effects may be expected from neighbouring engineering and other scientific fields. Three areas will be covered in a survey of nowadays use of stereological methods in civil engineering. However, the major contribution comes from building materials technology. New challenging areas in civil engineering, an increasing shortage of raw materials and strong developments in information technology will mark the route in the coming decades. As a consequence, civil engineers will be involved in major research efforts requiring a more extensive and frequent use of stereological techniques.
Key words: building materials, fluid and soil mechanics, stereology.

INTRODUCTION

Although morphometry has been already exercized for quite a long time in various fields of civil engineering, the use of stereological methods so far has stayed rather limited. This must be due to the relatively short research tradition in civil engineering and to the fact that the (interdisciplinar) literature on stereology is generally not scanned by or easily accessible to researchers in civil engineering.
Hence, a progress report on the influence of stereology on civil engineering research would be brief and therefore of limited interest.
Reference can be given here to such reports, the scope of which however is restricted to building materials, in particular to the cementitious ones (Stroeven, 1982, 1986).
Building materials technolgy is an integral part of materials science. Since stereological techniques are sometimes frequently used in neighbouring branches of materials science, they succeed in gradually entering also the civil engineering field. Some areas of civil engineering are showing overlap with connected areas in other engineering branches or even with areas in biology and medicines. Since stereology is widely used in these areas it may also have a fertilizing effect on its use in civil engineering.

CIVIL ENGINEERING

"Civil engineering is the principal instrument for focussing man's scientific and technological skills on the creation of constructed facilities which advance a society towards the attainment of such basic objectives as economic development, environmental protection and social well-being" (MIT brochure).
For the realization of the constructed facilities natural materials are used such as rock, gravel, sand, clay, wood, etc., as well as man-made materials such as concrete, bricks and steel. The constructed facilities, first of all, have to fulfil their direct functional purposes. However, they have to offer protection against calamities as well.
Civil engineers are employing the four classical elements, soil, water, air and fire (Empedocles, around 400 BC) to create the constructed facilities. The natural forces trying to restore the original equilibrium in nature are formed by the same elements; earth-quakes, storms and floods are the direct manifestation of such forces. Abrasion, erosion and corrosion are acting in a more stealthy way.
I man's struggle with nature for survival and for maintenance of the constructed facilities, research will play an essential role, even in civil engineering. Moreover, we may expect the built environment to expand to "new" areas such as the sea or ocean floor and outer space. Particularly, civil engineers will be involved in the first field.
Challenging at the moment is the first step in that direction, the off-shore engineering. The struggle between men and the sea is getting new dimensions; off-shore platforms for gas and oil exploration have already given a new impetus to the creative potentialities of civil engineers and, as a consequence, to research. A more fundamental study of the building materials but of the sea as well is the logical result. Huge civil engineering problems are additionally situated in the coastal areas, particularly in the deltas of rivers. Special problems are arising from a raising of the sea level often in combination with a declining of the land (Venice, Bangkok).
Sanitary engineering is widening its scope towards environmental engineering. In cooperation with representatives from the bio-medical sciences, civil engineers have to cope with increasingly complex environmental problems in human society, concerned with air, water and soil pollution endangering the assessment of water quality for human consumption or irrigation purposes.
In the coming decades civil engineers will be confronted with the restricted availability of raw materials. The pressure to use waste materials and to recycle building materials to an ever increasing degree will steadily be growing. This will give rise to new material concepts in civil engineering. In order to master these problems in the challenging world of tomorrow, the civil engineer definitely will have to rely more strongly on scientific research.
In studying the combined forces of the four classical elements, the researchers certainly will be in need of stereological tools.
Access to the relevant stereological literature sources will be simplified by appropriate computer facilities. As a consequence even civil engineers will be put in a position to get acquainted with the full

potentialities of stereological methods. On short notice one may expect fertilizing effects on building materials technology and geotechnical engineering due to parallelling research efforts in more advanced fields such as metallurgy and ceramics technology where stereological techniques are widely used.

This contribution will illustrate by representative examples the principal applications of stereological methods in civil engineering. It will cover fluid mechanics, geotechnical engineering and building materials technology. It will not aim for completeness, though. Most probably, future applications can be expected in the field of environmental engineering as well. However, these applications are considered to be more typical for scientific fields such as bio-chemistry or medicines.

FLUID MECHANICS

Water and wind can combine their destructive power in an optimum way in the off-shore field (fig. 1). Wave loading is therefore a major design parameter for constructed facilities at the sea or ocean surface level. At the border of the off-shore field, water and wind tend to change coastal lines.

Therefore wave patterns are the subject of interest to researchers in fluid mechanics. Two essentially different approaches are available to determine the surface morphology or surface texture, i.e. stereophotography and echo sounding scanning techniques. The first full-field approach would basically allow for reconstruction of the surface texture in a deterministic sense (Holthuijsen, 1983). The second technique could only lead to a similar result if systematic scanning of profiles at high speed could be achieved. A large degree of resemblance with serial sectioning (of materials or tissues) can be noticed in the latter case. A random set of profiles recorded at the "same" moment would allow deter-

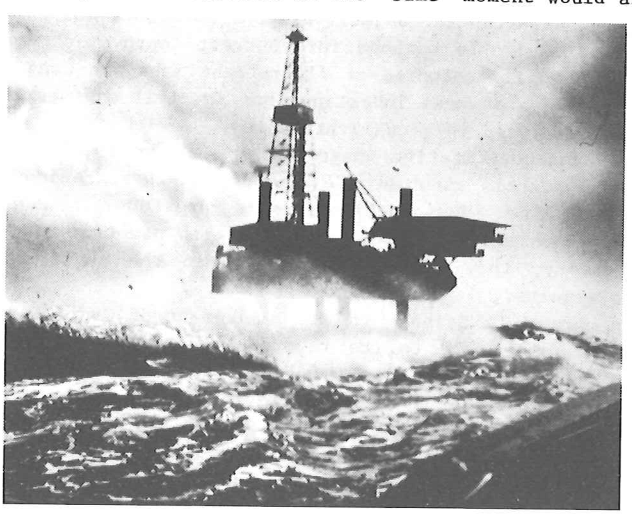

Fig. 1 Off-shore platform in hostile environment.

mining the geometrical statistical properties of the three-dimensional field of wave surfaces. Under certain assumptions a single profile could suit that purpose too. A similar approach has been developed for fractography in metallurgy by e.g. Underwood and Banerji (1983).
As an example of such use of stereological techniques we can here refer to sea surface elevation measurements performed by Hasle and Stansberg (1984) in a wave tank along straight transects having constant angular spacing. They determined the spatial covariance function of surface elevations along the transects, i.e. in a system of polar coordinates. To obtain the two-dimensional frequency-directional spectrum they used a conventional two-dimensional Fourier transformation which is performed in Cartesian coordinates. Holthuijsen and Booij (1986) refined this approach by avoiding the transformation from Cartesian to polar coordinates and vica versa.
This type of problems is showing similarity with the stereological problem solved by Hilliard (1962). He related the orientation distribution of surfaces in space to the orientation distribution of their line intersections in a sectional plane. This author has employed this technique for analysing the extent of microfissuring of concrete; this subject will be treated in the next chapter.

BUILDING MATERIALS

Stereological techniques for materials science purposes have mainly been developed in metallurgy. These tools can of course be employed equally well for research applications in building materials technology. However, in most cases, the tools needed adjustment for the special application.
Concrete always contains a vast amount of micro cracks; the number of cracks in virgin specimens may amount to 50% or more of those present at rupture. An increase in total crack length is mostly associated with a reduction in residual strength. Objective means for crack morphometry are therefore required. Suitable methods for contrast improvement are coming from petrography. Usually coloured or fluorescent inks are used for that purpose. Unfortunately, in most investigations in civil engineering crack patterns are only analysed in a qualitative way.
An example of a semi-quantitative image analysis is presented by Gjorv & Shah (1971). The authors counted the number of intersections with a superimposed test line. The specimens were previously subjected to durability tests. Cracks were visualized by red ink penetration. Applying stereological theory, they could have determined the specific surface area from their results.
In the Group of Materials Science in the Department of Civil Engineering much attention has been paid to the recording of microcracking in concrete specimens subjected to a certain loading regime. Fig. 2 gives an example of a section image of a specimen previously loaded to a low-cycle fatigue loading up to final rupture. After cutting and grinding the specimen, the surface of the specimen was sprayed with a fluorescent oil. The fine organo-metallic particles in the oil formed a line delineation along the tiny cracks after absorption of the oil by the cracks. The recording was accomplished by photographing under UV-illumination. The recording on slide was projected on a semi-transparent screen, whereupon

the cracks were manually copied. The pattern shown in Fig. 2 at the right presents an example. The width of the image pattern is roughly 100 mm. The photograph at the left is revealing only a part of the sampled image. Although the fluctuating compressive load acted in the vertical direction, partial orientation of the cracks in the vertical direction is not too obvious. Also, no continuous (macro)cracks were disposed despite loading up to the final rupture stage. The quantitative data on crack morphology demonstrated that a major part of all cracks had already been formed in the virgin specimen (due to shrinkage). This sort of approach allowed the detection of the successive fracture mechanisms on the sub-macroscopical level in the concrete specimens subjected to different loading amplitudes and frequencies (Reinhardt, et al, 1978; Stroeven, 1978).

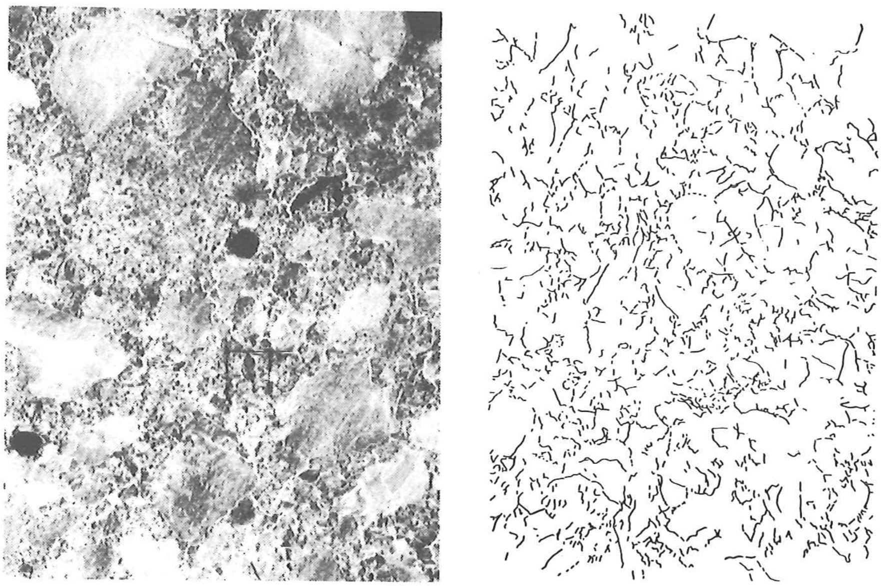

Fig. 2 Application of a stereological method for quantitative image analysis to plain concrete. At the left, the section image is shown. Cracks are visualized by means of the filtered particle technique. At the right, a manually copied pattern of the surface cracks is presented. The photograph at the left reveals a detail of the image.

To that end, the specific surface area of the cracks was determined by Saltikov's directed secants technique. By repeating the procedure, full insight into the crack orientation distribution could be obtained.
New types of concrete are being brought onto the market, among them fibre

reinforced concretes. Fibres are improving strength and particularly toughness. Due to fabrication and densification techniques the fibre structure is revealing segregation and partial orientation (Fig. 3). The present author developed the framework for reconstructing the 3-D features of steel fibre reinforced concrete (SFRC) from measurements in the section or projection (X-ray radiograph) plane. A combination of independent observations can suit the purpose. Feature counts or intersection counts in the projection plane are forming the stereological basis (Stroeven, 1981). Quite independently, Kasperkiewicz, et al. (1978) have developed geometrical-statistical formulas to define fibre spacing in particular for thin elements. Results are identical for similar cases. On the same macroscopical level other outgrowth of metallographic techniques can be classified. The objectives are to analyse the distribution of particles in space. To that end, this author used mono-sized ceramic spheres (Fig. 4, on the left) (Stroeven, 1973). Areal, lineal and random secants analyses were executed. Similar problems were faced by Pigeon (1969). However, he used glass marble aggregate for this purpose. Moreover, unaware of stereology, he experimentally derived a relationship between areal and volume fractions. Gast (1975) dealt with the problem of particle dispersion in concrete analogously to pore size distribution problems. Karl & Wu (1970) studied the effect of vibration techniques on grain inhomogeneity and anisometry. To that end sections of cubes were examined. The effect of the vibration technique was convincingly demonstrated. Quantitative analysis incorrectly assumed the particle size distribution to be directly governed by the observed section size distribution. Anisometry was determined by measuring the principal directions of all grain sections. Saltikov's method of directed secants could have proved its value. Well-developed are applications to pore size analysis in concrete. Air entrainment is employed to obtain durable concrete. Pores are spherical in such cases (Fig. 4, on the right).

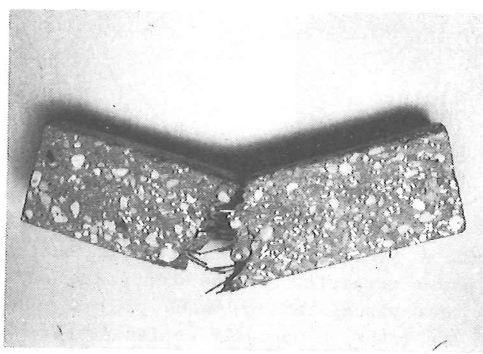

Fig. 3 Application of stereological methods for quantitative image analysis of SFRC. A section image - the surface of a three-point bending specimen - is presented, revealing fibre segregation and partial orientation. Specimen size is 40 mm x 40 mm x 160 mm.

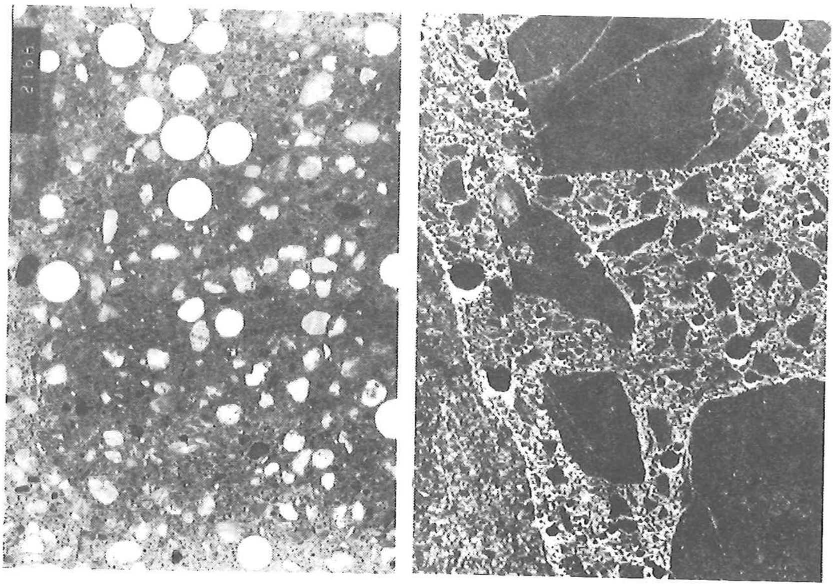

Fig. 4 Mono-sized spherical particles dispersed in a mortar matrix (at the left) and spherical pores due to air entrainment in a mortar matrix (at the right).

SOIL MECHANICS

Two types of problems dealt with in soil mechanics are involving stereological aspects. In both cases the material of interest is sand, or a sand-clay mixture. The sand particles are forming a skeletton with morphological characteristics of a geometrical-statistical nature.
The texture of such materials influences the mechanical behaviour. Hence, for formulating the constitutive relationships it would be necessary to incorporate a suitable measure for the textural properties. Stress in such a discontinuous material is to be interpreted on the physical level as a volume average of a series of contact forces between individual particles. The resulting stress vector in a section is influenced by the magnitude and orientation of the contact forces in a certain volume element. Stable values are obtained when a representative volume element is sampled.
Structure-sensitive properties are however depending on local morphological features, i.e. on details of the texture. Presenting theoretical details of such an approach would go too far. The interested reader may be referred to work by Oda, et al (1982). This approach could also be followed in the case of a crystalline material, e.g. granites are showing similar mechanical behaviour as concretes.
Although most of the applications are lying outside the field of civil

engineering, we may refer to the description for cracked rock masses. Oda (1982) defined a fabric tensor as the weighed orientation distribution function of all cracks intersecting a scanning line. The weight factor is the crack size. His approach is of a pure stereological nature. This application for crack analysis is nicely complementing work by this author presented in the previous chapter. Close similarity can also be indicated with fractographical work in metallography (Underwood and Banerji, 1983; Karlsson, 1986), where - as in the described fluid mechanics case - the problem of completely describing non-planar surfaces is arising. The problem of relating the 3-D orientation distribution of surfaces in space to the 2-D distribution of traces in a section plane is also treated by Hilliard (1962) as we have mentioned before.
Tests have been performed on 2-D systems of plastic discs as a simulation of a granular material like sand. By selecting photoelastic materials, full-field information could be obtained on the contact forces, so that stresses and strains could be determined for arbitrary elements.

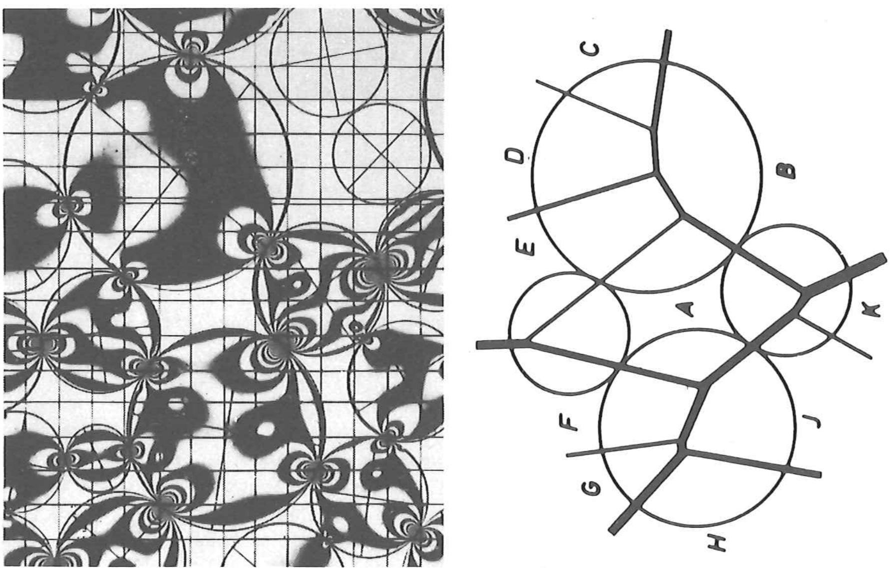

Fig. 5 Photoelastic solution for stresses in 2-D model of discs (at the left) and internal force pattern (at the right). The width of the straight line is proportional to the magnitude of the contact force.

According to this author's knowledge, trials for a 3-D interpretation on the basis of stereological notions have not been made so far. Early work is performed, e.g. by de Josselin de Jong and Verruijt (1969) (Fig. 5).
Another type of quasi-stereological problem is met in the analysis of surface deformation patterns of granular materials. In plain strain situations we are twice recording the surface of a granular material, once in undeformed and once in deformed situation.

Observation of two "point" patterns simultaneously in a stereoscope is leading to an image with "depth". The depth can be analysed giving a solution for the deformation pattern at the surface of the material. In the case of a parallellepiped (sand block) under combined normal and shear loading a saddle-like (anti-clastic) surface is being observed. Direct superposition of the two images would give rise to a moiré picture, revealing hyperbolic lines showing the principal direction of the surface deformations (de Josselin de Jong, 1968).

CONCLUSIONS

In different fields of civil engineering the problem of analysing non-planar surfaces is met. Either by stereophotography or by line scanning techniques this problem can be, and actually is, solved. Examples have been presented from fluid and soil mechanics. Problems concerned with the interpretation of 2-D information in terms of 3-D features of an actual material are encountered in building materials technology. A series of examples is touched upon. Two representative examples have been elaborated more extensively. Stereological tools are playing an important role in finding solutions to the posed problems. Since various fields of civil engineering, among which those treated, are neighbouring such fields in which sometimes stereological notions are more widespread, in the coming decades it can be expected that stereology will be used more extensively in civil engineering too.

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