GATE Study Material

Surveying (Civil Engineering)

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Basic concepts of surveying

The aim of this chapter is to introduce the reader to the basic concepts of surveying. It is therefore the most important chapter and worthy of careful study and consideration.

1.1 DEFINITION

Surveying may be defined as the science of determining the position, in three dimensions, of natural and man-made features on or beneath the surface of the Earth. These features may then be represented in analog form as a contoured map, plan or chart, or in digital form as a three-dimensional mathematical model stored in the computer. This latter format is referred to as a *digital ground model* (DGM).

In engineering surveying, either or both of the above formats may be utilized in the planning, design and construction of works, both on the surface and underground. At a later stage, surveying techniques are used in the dimensional control or setting out of the designed constructional elements and also in the monitoring of deformation movements.

In the first instance, surveying requires management and decision making in deciding the appropriate methods and instrumentation required to satisfactorily complete the task to the specified accuracy and within the time limits available. This initial process can only be properly executed after very careful and detailed reconnaissance of the area to be surveyed.

When the above logistics are complete, the field work – involving the capture and storage of field data – is carried out using instruments and techniques appropriate to the task in hand.

The next step in the operation is that of data processing. The majority, if not all, of the computation will be carried out by computer, ranging in size from pocket calculator to mainframe. The methods adopted will depend upon the size and precision of the survey and the manner of its recording; whether in a field book or a data logger. Data representation in analog or digital form may now be carried out by conventional cartographic plotting or through a totally automated system using a computer-driven flat-bed plotter. In engineering, the plan or DGM is used for the planning and design of a construction project. This project may comprise a railroad, highway, dam, bridge, or even a new town complex. No matter what the work is, or how complicated, it must be set out on the ground in its correct place and to its correct dimensions, within the tolerances specified. To this end, surveying procedures and instrumentation are used, of varying precision and complexity, depending on the project in hand.

Surveying is indispensable to the engineer in the planning, design and construction of a project, so all engineers should have a thorough understanding of the limits of accuracy possible in the construction and manufacturing processes. This knowledge, combined with an equal understanding of the limits and capabilities of surveying instrumentation and techniques, will enable the engineer to successfully complete his project in the most economical manner and shortest time possible.

1.2 BASIC MEASUREMENTS

Surveying is concerned with the fixing of position whether it be control points or points of topographic detail and, as such, requires some form of reference system.

The physical surface of the Earth, on which the actual survey measurements are carried out, is mathematically non-definable. It cannot therefore be used as a reference datum on which to compute position.

An alternative consideration is a level surface, at all points normal to the direction of gravity. Such a surface would be formed by the mean position of the oceans, assuming them free from all external forces, such as tides, currents, winds, etc. This surface is called the geoid and is the equipotential surface at mean sea level. The most significant aspect of this surface is that survey instruments are set up relative to it. That is, their vertical axes, which are normal to the plate bubble axes used in the setting-up process, are in the direction of the force of gravity at that point. Indeed, the points surveyed on the physical surface of the Earth are frequently reduced to their equivalent position on the geoid by projection along their gravity vectors. The reduced level or elevation of a point is its height above or below the geoid as measured in the direction of its gravity vector (or plumb line) and is most commonly referred to as its height above or below mean sea level (MSL). However, due to variations in the mass distribution within the Earth, the geoid is also an irregular surface which cannot be used for the mathematical location of position.

The mathematically definable shape which best fits the shape of the geoid is an ellipsoid formed by rotating an ellipse about its minor axis. Where this shape is used by a country as the surface for its mapping system, it is termed the reference ellipsoid. *Figure 1.1* illustrates the relationship of the above surfaces.

The majority of engineering surveys are carried out in areas of limited extent, in which case the reference surface may be taken as a tangent plane to the geoid and the rules of plane surveying used. In other words, the curvature of the Earth is ignored and all points on the physical surface are orthogonally projected onto a flat plane as illustrated in *Figure 1.2*. For areas less than 10 km square the assumption of a flat Earth is perfectly acceptable when one considers that in a triangle of approximately 200 km^2, the difference between the sum of the spherical angles and the plane angles would be 1 second of arc, or that the difference in length of an arc of approximately 20 km on the Earth's surface and its equivalent chord length is a mere 10 mm.

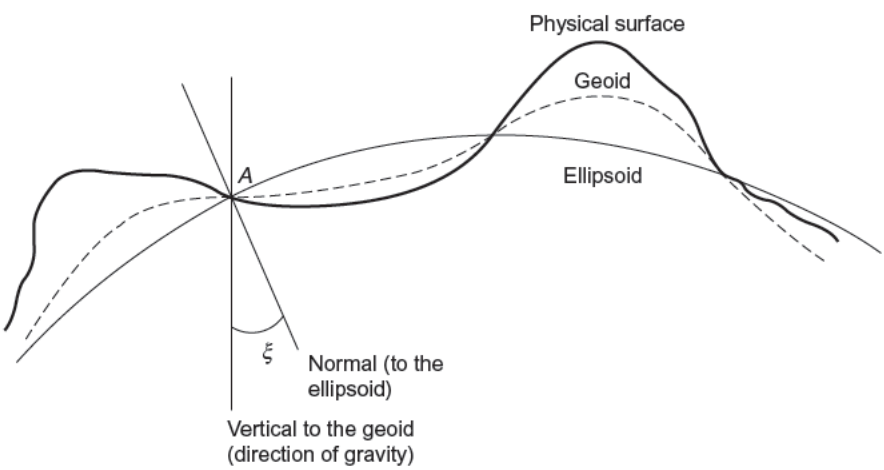

Fig. 1.1

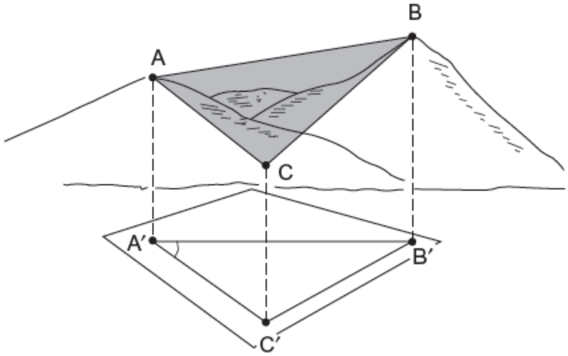

Fig. 1.2 *Projection onto a plain surface*

The above assumptions of a flat Earth are, however, not acceptable for elevations as the geoid would deviate from the tangent plane by about 80 mm at 1 km or 8 m at 10 km. Elevations are therefore referred to the geoid or MSL as it is more commonly termed. Also, from the engineering point of view, it is frequently useful in the case of inshore or offshore works to have the elevations related to the physical component with which the engineer is concerned.

An examination of *Figure 1.2* clearly shows the basic surveying measurements needed to locate points *A*, *B* and *C* and plot them orthogonally as *A*′, *B*′ and *C*′. In the first instance the measured *slant distance AB* will fix the position of *B* relative to *A*. However, it will then require the *vertical angle* to *B* from *A*, in order to reduce *AB* to its equivalent horizontal distance *A*′*B*′ for the purposes of plotting. Whilst similar measurements will fix *C* relative to *A*, it requires the *horizontal angle BAC* (*B*′*A*′*C*′) to fix *C* relative to *B*. The *vertical distances* defining the relative elevation of the three points may also be obtained from the slant distance and vertical angle (trigonometrical levelling) or by direct levelling (Chapter 2) relative to a specific reference datum. The five measurements mentioned above comprise the basis of plane surveying and are illustrated in *Figure 1.3*, i.e. *AB* is the slant distance, *AA*′ the horizontal distance, *A*′*B* the vertical distance, *BAA*′ the vertical angle (α) and *A*′*AC* the horizontal angle (θ).

It can be seen from the above that the only measurements needed in plane surveying are angle and distance. Nevertheless, the full impact of modern technology has been brought to bear in the acquisition and processing of this simple data. Angles are now easily resolved to single-second accuracy using optical and electronic theodolites; electromagnetic distance measuring (EDM)

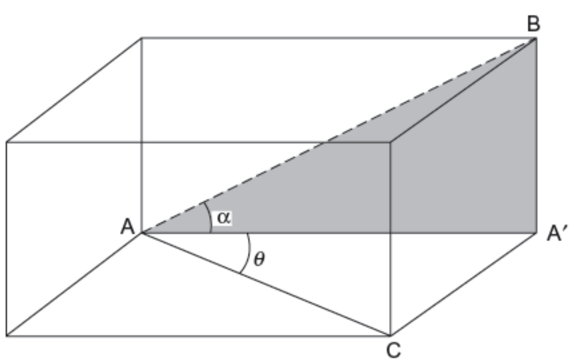

Fig. 1.3 *Basic measurements*

equipment can obtain distances of several kilometres to sub-millimetre precision; lasers and north-seeking gyroscopes are virtually standard equipment for tunnel surveys; orbiting satellites and inertial survey systems, spin-offs from the space programme, are being used for position fixing off shore as well as on; continued improvement in aerial and terrestrial photogrammetric equipment and remote sensors makes photogrammetry an invaluable surveying tool; finally, data loggers and computers enable the most sophisticated procedures to be adopted in the processing and automatic plotting of field data.

1.3 CONTROL NETWORKS

The establishment of two- or three-dimensional control networks is the most fundamental operation in the surveying of an area of large or small extent. The concept can best be illustrated by considering the survey of a relatively small area of land as shown in *Figure 1.4*.

The processes involved in carrying out the survey can be itemized as follows:

(1) A careful reconnaissance of the area is first carried out in order to establish the most suitable positions for the survey stations (or control points) *A*, *B*, *C*, *D*, *E* and *F*. The stations should be intervisible and so positioned to afford easy and accurate measurement of the distances between them. They should form 'well-conditioned' triangles with all angles greater than 45°, whilst the sides of the triangles should lie close to the topographic detail to be surveyed. If this procedure is adopted, the problems of measuring up, over or around obstacles, is eliminated.

The survey stations themselves may be stout wooden pegs driven well down into the ground, with a fine nail in the top accurately depicting the survey position. Alternatively, for longer life,

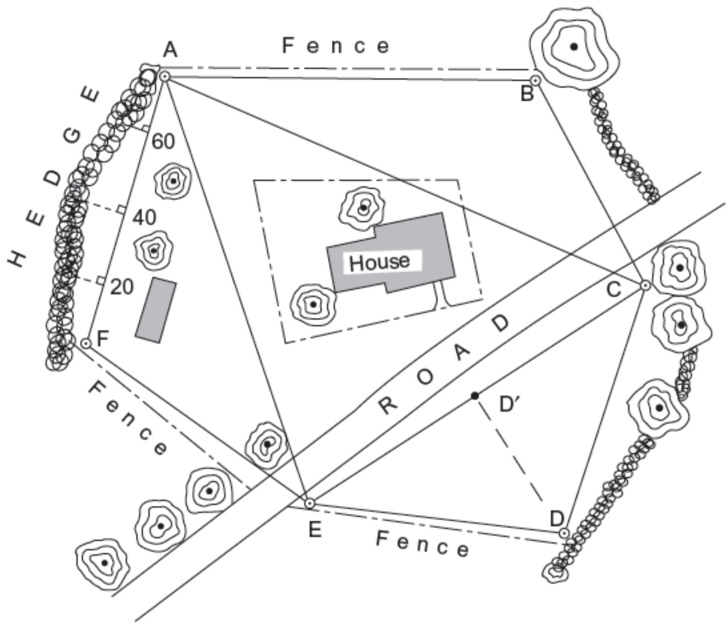

Fig. 1.4 *Linear survey*

concrete blocks may be set into the ground with some form of fine mark to pinpoint the survey position.

(2) The distances between the survey stations are now obtained to the required accuracy. Steel tapes may be laid along the ground to measure the slant lengths, whilst vertical angles may be measured using hand-held clinometers or Abney levels to reduce the lengths to their horizontal equivalents. Alternatively, the distances may be measured in horizontal steps as shown in *Figure 1.5*. The steps are short enough to prevent sag in the tape and their end positions at 1, 2 and *B* fixed using a plumb-bob and an additional assistant. The steps are then summed to give the horizontal distances.

Thus by measuring all the distances, relative positions of the survey stations are located at the intersections of the straight lines and the network possesses shape and scale. The surveyor has thus established in the field a two-dimensional horizontal control network whose nodal points are positioned relative to each other. It must be remembered, however, that all measurements, no matter how carefully carried out, contain error. Thus, as the three sides of a triangle will always plot to give a triangle, regardless of the error in the sides, some form of *independent check* should be introduced to reveal the presence of error. In this case the horizontal distance from *D* to a known position *D′* on the line *EC* is measured. If this distance will not plot correctly within triangle *CDE*, then error is present in one or all of the sides. Similar checks should be introduced throughout the network to prove its reliability.

(3) The proven network can now be used as a reference framework or huge template from which further measurements can now be taken to the topographic detail. For instance, in the case of line *FA*, its position may be physically established in the field by aligning a tape between the two survey stations. Now, offset measurements taken at right angles to this line at known distances from *F*, say 20 m, 40 m and 60 m, will locate the position of the hedge. Similar measurements from the remaining lines will locate the position of the remaining detail.

The method of booking the data for this form of survey is illustrated in *Figure 1.6*. The centre column of the book is regarded as the survey line *FA* with distances along it and offsets to the topographic detail drawn in their relative positions as shown in *Figure 1.4*.

Note the use of oblique offsets to more accurately fix the position of the trees by intersection, thereby eliminating the error of estimating the right angle in the other offset measurements.

The network is now plotted to the required scale, the offsets plotted from the network and the relative position of all the topographic detail established to form a plan of the area.

(4) As the aim of this particular survey was the production of a plan, the accuracy of the survey is governed largely by the scale of the plan. For instance, if the scale was, say, 1 part in 1000, then a plotting accuracy of 0.1 mm would be equivalent to 100 mm on the ground and it would not be economical or necessary to take the offset measurements to any greater accuracy than this. However, as the network forms the reference base from which the measurements are taken, its position would need to be fixed to a much greater accuracy.

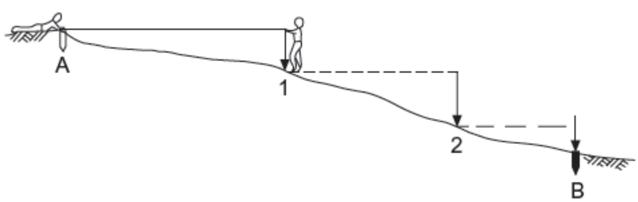

Fig. 1.5 *Stepped measurement*

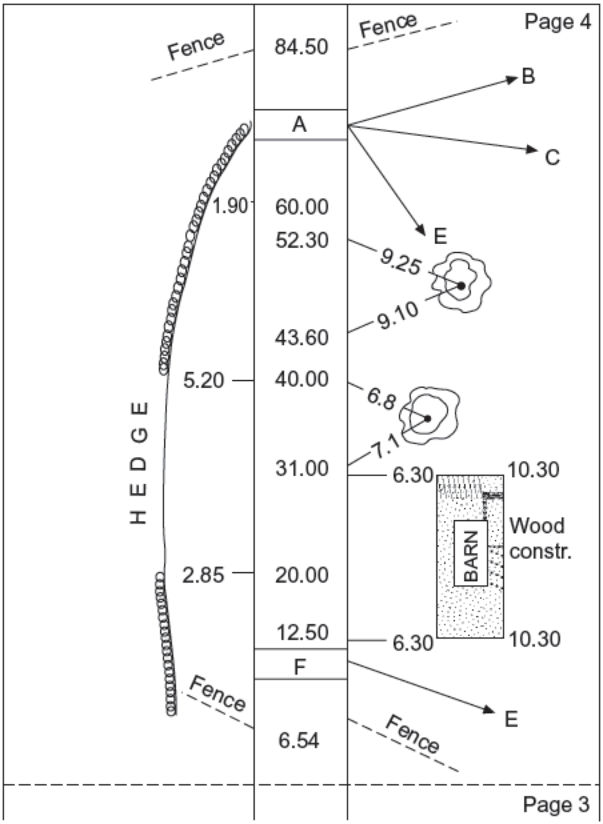

Fig. 1.6 *Field book*

The above comprises the steps necessary in carrying out this particular form of survey, generally referred to as a linear survey. It is naturally limited to quite small areas, due to the difficulties of measuring with tapes and the rapid accumulation of error involved in the process. For this reason it is not a widely used surveying technique. It does, however, serve to illustrate the basic concepts of all surveying in a simple, easy to understand manner.

Had the area been much greater in extent, the distances could have been measured by EDM equipment; such a network is called a *trilateration*. A further examination of *Figure 1.4* shows that the shape of the network could be established by measuring all the horizontal angles, whilst its scale or size could be fixed by a measurement of one side. In this case the network would be called a *triangulation*. If all the sides and horizontal angles are measured, the network is a *triangulateration*. Finally, if the survey stations are located by measuring the adjacent angles and lengths shown in *Figure 1.7*, thereby constituting a polygon *A*, *B*, *C*, *D*, *E*, *F*, the network is a *traverse*. These then constitute all the basic methods of establishing a horizontal control network, and are dealt with in more detail in Chapter 6.

1.4 LOCATING POSITION

The method of locating the position of topographic detail by right-angled offsets from the sides of the control network has been mentioned above. However, this method would have errors in establishing

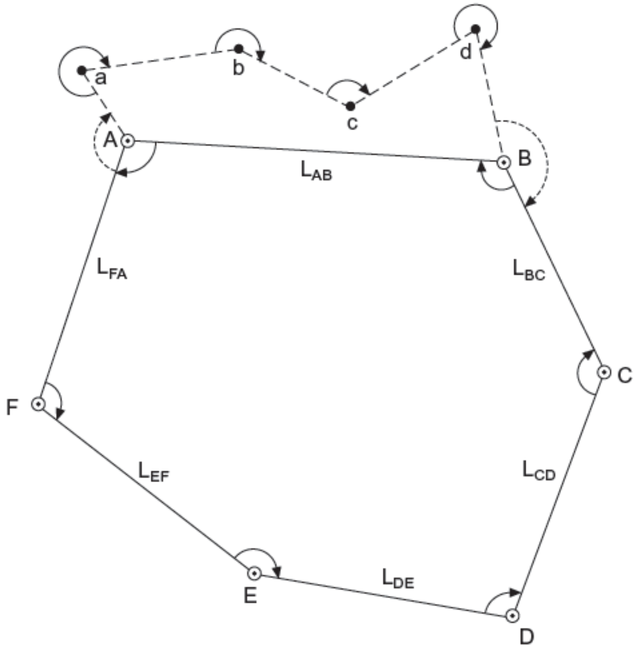

Fig. 1.7 *Traverse*

the line *FA*, in setting out the right angle (usually by eye) and in measuring the offset. It would therefore be more accurate to locate position directly from the survey stations. The most popular method of doing this is by polar coordinates as shown in *Figure 1.8*. *A* and *B* are survey stations of known position in a control network, from which the measured horizontal angle *BAP* and the horizontal distance *AP* will fix the position of point *P*. There is no doubt that this is the most popular method of fixing position, particularly since the advent of EDM equipment. Indeed, the method of traversing is a repeated application of this process.

An alternative method is by intersection where *P* is fixed by measuring the horizontal angles *BAP* and *ABP* as shown in *Figure 1.9*. This method forms the basis of triangulation. Similarly, *P* may be fixed by the measurement of horizontal distances *AP* and *BP* and forms the basis of the method of

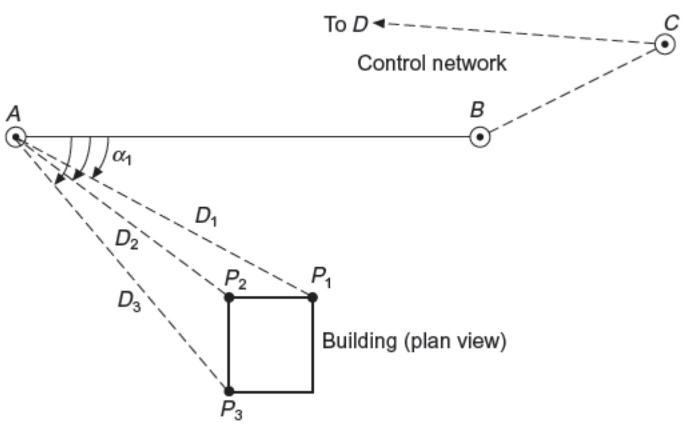

Fig. 1.8 *Polar coordinates*

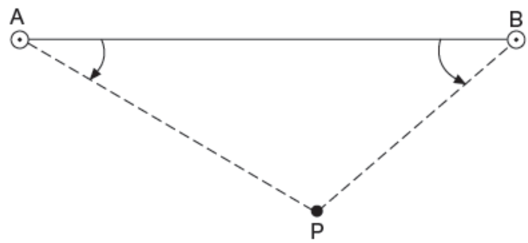

Fig. 1.9 *Intersection*

trilateration. In both these instances there is no independent check as a position for *P* (not necessarily the correct one) will always be obtained. Thus at least one additional measurement is required either by combining the angles and distances (triangulateration) by measuring the angle at *P* as a check on the angular intersection, or by producing a trisection from an extra control station.

The final method of position fixing is by resection (*Figure 1.10*). This is done by observing the horizontal angles at *P* to at least three control stations of known position. The position of *P* may be obtained by a mathematical solution as illustrated in Chapter 6.

Once again, it can be seen that all the above procedures simply involve the measurement of angle and distance.

1.5 LOCATING TOPOGRAPHIC DETAIL

Topographic surveying of detail is, in the first instance, based on the established control network. The accurate relative positioning of the control points would generally be by the method of traversing or a combination of triangulation and trilateration (Chapter 6). The mean measured angles and distances would be processed, to provide the plane rectangular coordinates of each control point. Each point would then be carefully plotted on a precisely constructed rectangular grid. The grid would be drawn with the aid of a metal template (*Figure 1.11*), containing fine drill holes in an exact grid arrangement. The position of the holes is then pricked through onto the drawing material using the precisely fitting punch shown. Alternatively, the grid would be drawn using a computer-driven coordinatorgraph on a flat-bed or drum plotter. The topographic detail is then drawn in from the plotted control points which were utilized in the field.

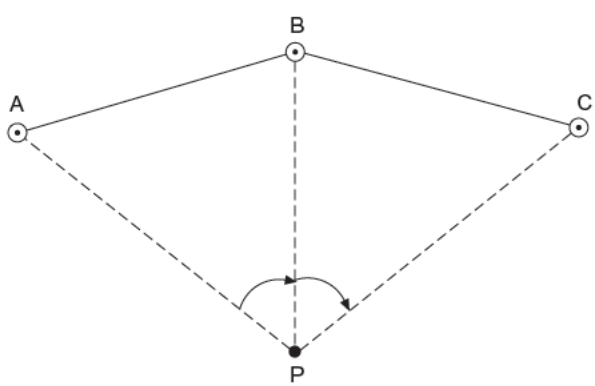

Fig. 1.10 *Resection*

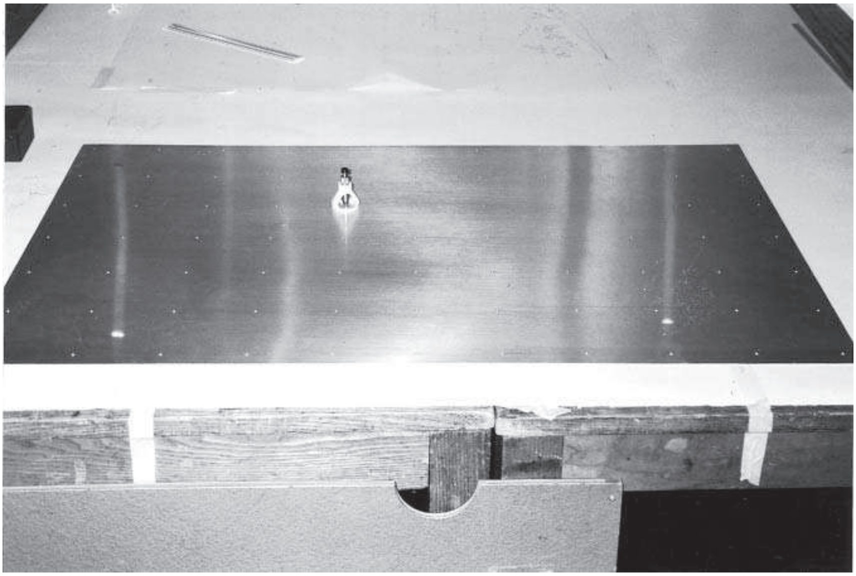

Fig. 1.11 *Metal template and punch*

1.5.1 Field survey

In the previous section, the method of locating detail by offsets was illustrated. In engineering surveys the more likely method is by polar coordinates, i.e. direction relative to a pair of selected control points, plus the horizontal distance from one of the known points, as shown in *Figure 1.8*.

The directions would be measured by theodolite and the distance by EDM, to a detail pole held vertically on the detail (*Figure 1.12)*; hence the ideal instrument would be the electronic tacheometer or total station.

The accuracy required in the location of detail is a function of the scale of the plan. For instance, if the proposed scale is 1 in 1000, then 1 mm on the plan would represent 1000 mm on the ground. If the plotting accuracy was, say, 0.2 mm, then the equivalent field accuracy would be 200 mm and distance need be measured to no greater accuracy than this. The equivalent angular accuracy for a length of sight at 200 m would be about 3′ 20″. From this it can be seen that the accuracy required to fix the position of detail is much less than that required to establish the position of control points. It may be, depending on the scale of the plan and the type of detail to be located, that stadia tacheometry could be used for the process, in the event of there being no other alternative.

The accuracy of distance measurement in stadia tacheometer ($D = 100 \times S \cos^2 \theta$), as shown in Chapter 2, is in the region of 1 in 300, equivalent to 300 mm in an observation distance of 100 m. Thus before this method can be considered, the scale of the plan must be analysed as above, the average observation distance should be considered and the type of detail, hard or soft, reconnoitred. Even if all these considerations are met, it must be remembered that the method is cumbersome and uneconomical unless a direct reading tacheometer is available.

1.5.2 Plotting the detail

The purpose of the plan usually defines the scale to which it is plotted. The most common scale for construction plans is 1 in 500, with variations above or below that, from 1 in 2500 to 1 in 250.

The most common material used is plastic film with such trade names as ‘Permatrace’. This is an

Fig. 1.12 '*Detail pole*' *locating topographic detail*

extremely durable material, virtually indestructible with excellent dimensional stability. When the plot is complete, paper prints are easily obtained.

Although the topographic detail could be plotted using a protractor for the direction and a scale for the distances, in a manner analogous to the field process, it is a trivial matter to produce 'in-house' software to carry out this task. Using the arrangement shown in *Figure 1.13*, the directions and distances are input to the computer, changed to two-dimensional coordinates and plotted direct. A simple question asks the operator if he wishes the plotted point to be joined to the previous one and in this way the plot is rapidly progressed. This elementary 'in-house' software simply plots points and lines and the reduced level of the points, where the vertical angle is included. However, there is now an abundance of computer plotting software available that will not only produce a contoured plot, but also supply three-dimensional views, digital ground models, earthwork volumes, road design, drainage design, digital mapping, etc.

1.5.3 Computer systems

To be economically viable, practically all major engineering/surveying organizations use an automated plotting system. Very often the total station and data logger are purchased along with the computer hardware and software, as a total operating system. In this way interface and adaptation problems are precluded. *Figure 1.14* shows such an arrangement including a 'mouse' for use on the digitizing tablet. An AO flat-bed plotter is networked to the system and located separately.

The essential characteristics of such a system are:

(1) Capability to accept, store, transfer, process and manage field data that is input manually or directly from an interfaced data logger (*Figure 1.15*).
(2) Software and hardware to be in modular form for easy accessing.
(3) Software to use all modern facilities, such as 'windows', different colour and interactive screen graphics, to make the process user friendly.
(4) Continuous data flow from field data to finished plan.

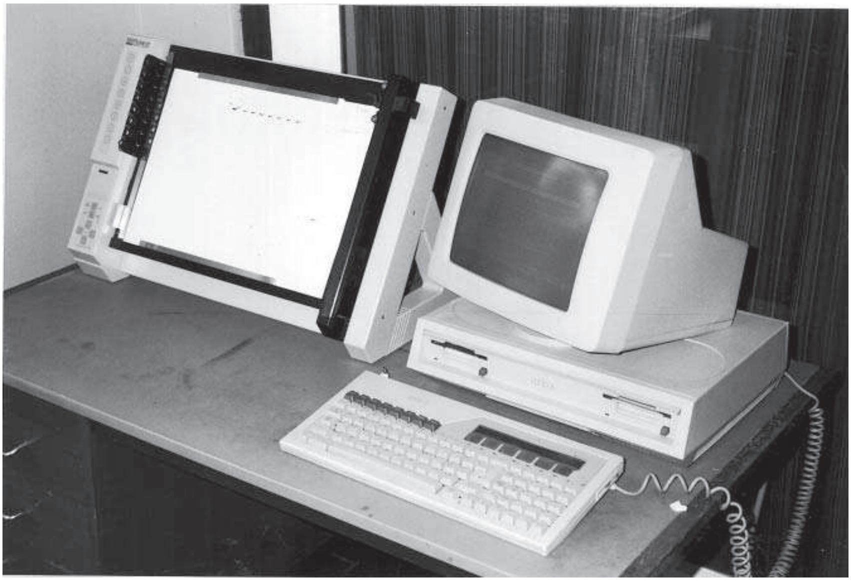

Fig. 1.13 *Computer driven plotter*

Fig. 1.14 *Computer system with digitizing tablet*

(5) Appropriate data-base facility, for the storage and management of coordinate and cartographic data necessary for the production of digital ground models and land/geographic information systems.
(6) Extensive computer storage facility.
(7) High-speed precision flat-bed or drum plotter.

Fig. 1.15 *Data logger*

To be truly economical, the field data, including appropriate coding of the various types of detail, should be captured and stored by single-key operation, on a data logger interfaced to a total station. The computer system should then permit automatic transfer of this data by direct interface between the logger and the system. The modular software should then: store and administer the data; carry out the mathematical processing, such as network adjustment, production of coordinates and elevations; generate data storage banks; and finally plot the data on completion of the data verification process.

Prior to plotting, the data can be viewed on the screen for editing purposes. This can be done from the keyboard or by light pen on the screen using interactive graphics routines. The plotted detail can be examined, moved, erased or changed, as desired. When the examination is complete, the command to plot may then be activated. *Figure 1.16* shows an example of a computer plot.

1.5.4 Digital ground model (DGM)

A DGM is a three-dimensional, mathematical representation of the landform and all its features, stored in a computer data base. Such a model is extremely useful in the design and construction process, as it permits quick and accurate determination of the coordinates and elevation of any point.

The DGM is formed by sampling points over the land surface and using appropriate algorithms to process these points to represent the surface being modelled. The methods in common use are modelling by 'strings', 'regular grids' or 'triangular facets'. Regardless of the methods used, they will all reflect the quality of the field data.

A 'string' comprises a series of points along a feature and so such a system stores the position of features surveyed. It is widely used for mapping purposes due to its flexibility, its accuracy along the string and its ability to process large amounts of data very quickly. However, as it does not store the relationship between strings, a searching process is essential when the levels of points not

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