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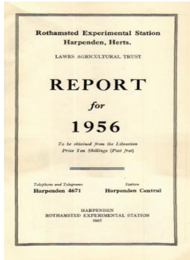
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SOIL STRUCTURE

By

W. W. Emerson

Introduction

The basic problem of soil structure consists in finding out how the individual constituents of soil crumbs, such as sand, clay and organic matter, are bonded together. The nature and number of these bonds will determine the strength of the crumbs. This, in turn, will decide if the surface soil pans under the mechanical action of falling raindrops, whether the soil is free draining and the ease of cultivation. The Physics Department has been particularly interested in the improvement of the structure of clay soils after a period under grass. One of the improvements is known to be an increase in the resistance of the crumbs to breakdown in water, and the problem has been to measure this increase in such a way as to offer some clue as to the mechanism by which it is brought about.

Previous workers have used two main methods. In the first, originated by Tiulin (1928), the dry crumbs were placed on top of a bank of sieves, wetted and the size distribution of the wetted crumbs determined after agitating the sieves under water. The second way, due to Middleton (1931), instead of reducing mechanical breakdown after wetting to a minimum, measures the degree of dispersion produced by a given amount of mechanical action. This is usually done by shaking the crumbs in water in an end-over-end shaker for a fixed time. There are two causes of crumb breakdown in both these methods: the initial breakdown on wetting the air-dry crumbs with water, usually called slaking, and the subsequent mechanical attrition of the crumbs. Slaking is due both to swelling of the clay on wetting, which may in extreme cases lead to dispersion of the clay, and also to the explosive action of entrapped air. The severity of the initial breakdown of the crumbs will clearly depend on the rate of wetting, and this was the first aspect of crumb breakdown which was investigated (Emerson and Grundy, 1954).

Crumb Breakdown Due to Slaking

Columns of soil about 8 cm. high consisting of 2–5 mm. air-dry crumbs were wetted with distilled water at different rates by means of capillary-tube siphons of different diameter. Check columns were also wetted under vacuum, which would prevent breakdown due to entrapped air. The cohesion of the wet crumbs was determined by measuring the height from which 40 drops of water would cause 0·15 g. out of approximately 1 g. of the wet crumbs to pass through a 1·2-mm.-aperture gauze. This technique was sufficiently gentle to avoid breakdown of the crumbs due to dispersion of the clay, and merely fractured the crumbs along planes of weakness produced during the initial wetting. Samples were taken from two adjoining plots on the Rothamsted Farm, containing 30 per cent clay, one under permanent grass and the other permanent arable which receives 14 tons dung/acre annually. The results showed that cohesion decreased sharply with rate of wetting, as expected, the decrease being more pronounced with the arable compared with the grassland crumbs. However, when wet at 0·2 cm./hr. rainfall, which is not often exceeded under the low-intensity rainfall in this part of England, the cohesion of the crumbs was not much lower than those wet under vacuum or extremely slowly. It was concluded, therefore, that slaking is not an important cause of crumb breakdown for this soil with these cropping treatments. This result is not generally valid, and slaking may be very severe with lighter soils. Extrapolating back to zero rate of wetting, the strength of the grassland crumbs was about twice that of the arable crumbs, showing that there must be an additional cohesive force present in the former.

Swelling of Soil Crumbs

A by-product of the preceding work was to demonstrate that the amount of water held by a soil at low suctions (up to about 200 cm. water) depended both on the rate at which the soil was wetted, because with rapid wetting more water could be accommodated along the planes of failure and, indirectly, on the length of time the soil was wet, because the swelling of the clay was found to take at least 24 hours. This latter point was later investigated in more detail (Emerson, 1955a). A clay crumb which had been dried to the wilting point (pF 4·2) was suspended on one arm of an analytical balance and slowly wetted using a capillary siphon, care being taken to prevent evaporation from the crumb. Although the crumb appeared to be completely wet after the first drop had appeared on the base of the crumb, in fact the crumb continued to increase in weight and was still doing so very slowly when the experiment was discontinued at the end of three months. Approximately 75 per cent of the total water uptake occurred in the initial wetting. Besides modifying the concept of field capacity, these results have an important bearing on the drainage of heavy clay soils when water percolates to the drains through fissures in the subsoil. The fissures will slowly close up during the winter as the clay swells, and since conduction depends on the fourth power of the radius, a small decrease in size will have a considerable effect on permeability. The more the subsoil is dried out during the summer, the more rapid will be the drainage the ensuing winter. One of the better crops for this purpose would be wheat, and the worst treatment a summer fallow. An analysis of Mr. Nicholson's results on the running of the mole drains on the Cambridge University Farm demonstrated this dependence of drain performance on summer cropping very elegantly.

Wet Strength of Crumbs

The next step was to investigate the second cause of crumb breakdown, i.e. disintegration of the wet crumbs. The two methods mentioned at the beginning determined the resistance of the wet crumbs to mechanical action, but it was thought that more controllable results might be obtained by using a " chemical hammer " on the crumbs in the following way. If two negatively charged plates (idealized clay crystals) are immersed in a salt solution there is a repulsive pressure between the plates due to the higher salt concentration between the plates than in the equilibrium solution outside, and this pressure increases as the salt concentration is reduced if the plates are a fixed distance apart. The pressure may be calculated using the simple Gouy theory, provided the plates are far enough apart. Therefore, by bringing crumbs into equilibrium with increasingly dilute salt solutions the weaker the attractive forces between the clay crystals, the greater will be the distance the crystals are forced apart, until eventually the crumbs fail and disperse. Unfortunately in the case of calcium saturated crumbs, which is effectively the English condition, the intrinsic short-range attractive forces between the clay crystals are sufficiently strong for the crumbs to remain stable even when percolated with distilled water. In water the calcium clay in the crumbs is in a metastable state of equilibrium, because if the crumbs are shaken the clay disperses, and a concentration of about 3 mM. $CaCl_2$ is needed before the clay will reflocculate. However, it was known that montmorillonite saturated with sodium would swell up spontaneously when brought into equilibrium with decreasing concentrations of sodium chloride (Hofmann and Bilke, 1936) until at a finite concentration of about 15 mN. the clay dispersed. This suggested that if the crumbs were first sodium saturated differences in the attractive forces between crumbs would be brought out.

In the initial experiments (Emerson, 1954a) a 1-cm. bed of 1–2 mm. air-dry crumbs was wetted with 500 mN. NaCl slowly under suction on a sintered-glass funnel to avoid breakdown due to slaking. After percolating with 500 mN. NaCl to displace all other exchangeable cations, successively more dilute salt solutions were percolated through, maintaining a constant hydrostatic head, and the decreases in permeability measured as functions of salt concentration in the leachate. The method was tried first on the Barnfield soil used in the earlier rate-of-wetting experiments. Two plots on Barnfield itself, 80, the unmanured plot, and 2N, receiving 14 tons dung annually, were compared with adjoining permanent grass, i.e., the same mineral constituents but different amounts of organic matter. The crumbs from 80 dispersed completely in 30 mN. NaCl, those from 2N in 5 mN., whereas the permeability of the grassland crumbs was still appreciable when percolated with distilled water. By contrast, on shaking the sodium-saturated crumbs into suspension it was found that the flocculating concentration of NaCl for the 80 plot was about the same as the dispersion concentration, but in the case of the grassland and 2N plots it was considerably higher, namely 250 mN. The organic matter present in the soil could therefore act both as a cementing agent for the flocculated clay in the crumbs and as a peptizer if the clay was brought into suspension.

In attempting to refine the technique it was found that an important part of the measured decrease in permeability was due to blockage of the pores in the sintered-glass funnel by dispersed clay and silt. This difficulty persisted even with coarser funnels, and it has only recently been overcome. In the method of test at present, a bed of 1–½-mm. glass spheres has been substituted for the sinter and the crumbs are brought into equilibrium with one concentration of NaCl only, namely 50 mN. At this concentration the Barnfield 80 crumbs, the weakest possible crumbs, collapse to form an impermeable bed, but no dispersed clay actually appears in the leachate, whereas the permeability of the corresponding permanent-grass crumbs remains unchanged.

To recapitulate, one of the reasons for developing the sodium method was to distinguish increased crumb stability, due to a slower rate of wetting when the crumbs are immersed in water, and a genuine increase, due to stronger attractive forces between the clay crystals in the crumbs. The former effect can be achieved by coating the crumbs with any substance which increases the contact angle of the crumbs with water.

Nature of the Organic Clay Complex

To obtain some insight into the way in which the organic matter stabilized the crumbs even after Na-saturation, the stabilization of crumbs and also pure clays by various substances of known chemical composition was investigated, since the organic matter appeared to stabilize the clay specifically (Emerson, 1956a). The first substances investigated were the polymers marketed for stabilizing crumbs, known as soil conditioners. These are of two kinds : the non-ionic polymers and carboxylated polymers. The simplest of the first is polyvinyl alcohol (PVA), repeating unit $-CH_2-CH(OH)-$, but natural substances such as dextrans may also be used. The second may be either of the linear ethylenic type, the simplest being polyacrylic acid (PAA), repeating unit $-CH_2-CH(COOH)-$, or polyuronides, such as sodium alginate or carboxymethyl cellulose. Small quantities of these substances in solution were mixed with Barnfield 80 soil to form a paste, which was then pushed through a 3-mm. sieve and finally dried to form synthetic crumbs. It was found that about 0·5 per cent by weight of polymer would confer maximum stability on the crumbs, i.e., no decrease in permeability occurred after percolating N/20-NaCl for 24 hours. The one exception was sodium alginate, which was only effective on soil which had been sodium saturated initially. This was ascribed to precipitation of the alginate as calcium alginate before it could become attached to the clay.

It was found that when crumbs stabilized with PVA and PAA were placed in water, after saturating with sodium, the former remained unaltered, whereas the latter swelled considerably. Flakes of Na-clay, to which small quantities of the two polymers had been added, behaved similarly (Emerson, 1955b). PAA was also effective at much lower concentrations than PVA. In particular for montmorillonite (Wyoming bentonite), 4 per cent PVA but only 0·25 per cent PAA were necessary to form stable Na-gels in water. By X-ray measurement of the dry flakes it was shown that PVA was linked to the planar faces of the crystallites to form an interlamellar complex. Unfortunately in the case of PAA, although an X-ray photograph of the dry flake was the same as an untreated

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flake, this was not sufficient evidence to infer that an interlamellar complex had not been formed, as there may have been insufficient regularly arranged crystals to give an X-ray reflexion. The carboxylated polymers would, of course, be expected to be repelled from the similarly charged planar faces. However, it has been found that crystals stabilized by very small quantities of an inter-lamellar complex forming substance can be distinguished by examination of thin sections of the swollen Na-montmorillonite gel under a polarizing microscope (Emerson, 1956c). In this way it has been possible to prove that the carboxylated polymers are not linked to the basal surfaces but must be linked to the edge faces.

The actual linkage depends on the proof by Schofield and Samson (1954) that the edge faces of kaolinite in addition to possessing a negative charge at high pH, due to dissociation of Si–OH groups, can become positively charged under acid conditions. From the similarity in crystal structure and from flocculation experiments, the edge faces of illite and montmorillonite must behave similarly. It is suggested that the polymers are linked by hydrogen bonds through the carboxyl groups to the oxygen and hydroxyls attached to aluminium atoms exposed at the edge faces, forming so-called peripheral complexes (Emerson, 1955b). Since the strength of the hydrogen bonds will depend on the readiness with which the edge faces and the dissociated carboxyl groups co-ordinate hydrogen ions, the efficiency of the polymers will depend both on the acidity and the pK of the carboxyl groups (Emerson, 1956a).

One important way in which the peripheral complexes may be distinguished from inter-lamellar complexes is that peripheral complexes may be dispersed by leaching with neutral pyrophosphate solution, while the latter are unaffected. The pyrophosphate ions displace the carboxyl groups. As a corollary, stable peripheral complexes could be equally well made with polyphosphates (Oplatka, 1954).

When the strength of crumbs from old grassland was measured after leaching with $0{\cdot}1M$-neutral pyrophosphate it was not much reduced, although an appreciable amount of organic matter was extracted (Bremner and Lees, 1955; Emerson, 1956b). It is concluded, therefore, that the fraction of the organic matter responsible for the increased crumb cohesion forms an inter-lamellar complex with the clay. After prolonged leaching with dilute alkali the strength of the grassland crumbs is reduced to that of Barnfield 80 crumbs. This contrasts with the stability of the PVA-stabilized crumbs, which are unaffected by alkali. However, inter-lamellar complexes made with gelatin slowly disperse if the pH is raised above the pK of the amino-groups, and by analogy it is suggested that the organic matter forms a polymeric inter-lamellar complex which depends partly for its strength on attraction between positively charged amino-groups and the negatively charged clay. The substance is thought to be polymeric because dispersion is slow and complexes formed with simple amino-acids disperse immediately the pH is raised sufficiently. If this is correct it could be an important source of nitrogen, which would be only slowly available, since it is known that the breakdown of substances is greatly reduced if sandwiched between clay particles (Ensminger and Gieseking, 1942).

Effect of Acidity on Crumb Strength

Reconsidering the first tests made with the sodium technique it was fortunate that the soil chosen, Barnfield, was buffered with free $CaCO_3$, for in acid soils increased stability may result from positive-edge to negative-face attraction. Crumbs taken from an acid arable field, Hoos, have been found to be much more stable than Barnfield 80 and, further, synthetic crumbs from the acid soil to which low-molecular-weight sodium alginate had been added were as unstable as the Barnfield soil (Emerson, 1956a). This makes it impossible at present in using the sodium technique to assess improvement in the wet strength of crumbs due to a ley unless the pH of the arable control is the same. It follows too that if liming improves soil structure it does not do so by increasing the wet strength of the crumbs. A possible way in which liming might be beneficial is if it maintains a sufficiently high concentration of Ca^{++} ions in the drainage water to ensure reflocculation of dispersed clay, provided at the same time the positive edges on the clay are neutralized by organic matter in solution. This is at present under investigation.

Until now it has been implied that if the clay fraction of the crumbs is stable, the crumbs themselves will be stable too. In other words, that clay–clay bonds are weaker than clay–sand bonds. Very little is known about the way clay is bonded to sand, but with our present techniques and knowledge of the forces exerted by clay particles, rapid progress should be possible.

Field Trials

Three groups of plots were sown in successive years to a variety of grasses and lucerne and with fallow strips as controls and left down for four years. Laboratory tests showed that the wet strength of the crumbs was appreciably increased by the grasses, particularly in the 0–2-inch layer. All the grasses were about equally effective, whereas lucerne had little effect. After ploughing up, heavy fertilizer dressings were given to minimize differences in the nutrient status of the plots, so that any difference in crop yield between the fallow and grass plots could be ascribed to structure. The first two blocks were sown in successive years to spring beans, winter wheat and spring barley. There was an increase in yield with the spring beans after grass, but unfortunately the yields were very low due to aphid attack. The only response with wheat and barley was an appreciable increase in yield of wheat after lucerne. This particular effect accords with results of ley–arable experiments elsewhere on the farm. This year on the third block, after ploughing up, the market-garden crops carrots and beet were sown. Immediately after germination, during prolonged dry weather, there was a spectacular increase in the rate of growth of carrots after grass, compared with the former lucerne and fallow plots. Later weather was particularly favourable for growth, and the final yield of carrots on the grass plots was not much higher. It appears, however, as though response to structure may be obtained from horticultural rather than agricultural crops.

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References

Bremner, J. M. & Lees, H. (1950). The extraction of organic matter from soil by neutral reagents. *J. agric. Sci.* **40**, 274.

Emerson, W. W. & Grundy, G. M. F. (1954). The effect of rate of wetting on water uptake and cohesion of soil crumbs. *J. agric. Sci.* **44**, 249.

Emerson, W. W. (1954a). The determination of the stability of soil crumbs. *J. Soil Sci.* **5**, 233.

Emerson, W. W. (1954b). The effect of various grasses and lucerne on the cohesion of soil crumbs. *Trans. 5th int. Congr. Soil Sci.* **2**, 65.

Emerson, W. W. (1955a). The rate of water uptake of soil crumbs at low suctions. *J. Soil Sci.* **6**, 147.

Emerson, W. W. (1955b). Complex formation between montmorillonite and high polymers. *Nature, Lond.* **176**, 461.

Emerson, W. W. (1956a). Synthetic soil conditioners. *J. agric. Sci.* **47**, 117.

Emerson, W. W. (1956b). A comparison between the mode of action of organic matter and synthetic polymers in stabilizing soil crumbs. *J. agric. Sci.* **47**, 350.

Emerson, W. W. (1956c). Liquid crystals of montmorillonite. *Nature, Lond.* **178**, 1248.

Ensminger, L. E. & Gieseking, J. E. (1942). Resistance of clay-adsorbed proteins to proteolytic hydrolysis. *Soil Sci.* **53**, 205.

Hofmann, U. & Bilke, W. (1936). On the intercrystalline swelling of montmorillonite. *Kolloidzschr.* **77**, 238.

Middleton, H. E. (1930). Properties of soil which influence soil erosion. *Tech. Bull. U.S. Dep. Agric.* 178.

Oplatka, A. (1954). *Disc. Faraday Soc.* **18**, 219 (quoted by Lifson).

Schofield, R. K. & Samson, H. R. (1954). Flocculation of kaolinite due to the attraction of oppositely charged crystal faces. *Disc. Faraday Soc.* **18**, 135.

Tiulin, A. F. (1928). Questions on soil structure. II. Aggregate analysis as a method for determining soil structure. *Results Invest. Dep. agric. Chem. Perm. agric. exp. Sta.* **2**, 77.

THE ELECTRONIC COMPUTER AT ROTHAMSTED

By

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Since a certain amount of mystery still surrounds electronic computers—typified by the practice of referring to them as " Giant Brains "—it may be well to start by considering in outline just what these computers do and how they do it. In brief, they are capable merely of performing the simplest arithmetical operations, such as addition, subtraction and multiplication; their essential feature is that they carry out these operations extremely fast and completely automatically.

Any computer can be divided into a number of parts. To begin with, there will be some kind of input and output devices to allow for communication with the outside world. By comparison with the speed of carrying out arithmetical operations, these devices are usually rather slow, and, to enable the machine to work at full speed, the numbers it uses as data and as intermediate results will be held in some kind of store into and out of which they can be moved at " electronic " speeds. There will be an arithmetic unit or " function box " which, on being supplied with two numbers, will produce their sum, difference or product, and some kind of control mechanism that will call up the correct numbers successively from the store and set the arithmetic unit to perform the correct functions on them.

To enable a computer to carry out a given piece of arithmetic, the latter must be broken down into a sequence of additions, subtractions and multiplications. Together these form a sequence of instructions to the machine, which is called a programme and is also held in the store. Even a simple sum, however, requires a large number of instructions, and various devices are resorted to in order to get round this difficulty. The most important of these is the machine's rudimentary power of discrimination; ordinarily, the machine obeys the instructions in a fixed order, but at given points it is able to inspect some current result and to obey one or other of two alternative instructions according as this result is zero or not (or is negative or not). Thus we might construct a sequence of instructions to carry out one cycle of an iterative approximation scheme. At the end of the sequence the machine inspects the difference between the approximation just obtained and the one obtained in the previous cycle; if this difference is not zero (to the order of accuracy required) it must return to an earlier instruction and repeat the iterative cycle, while if the difference is zero it can proceed to a different stage of the calculations.

Many calculations can be carried out by means of a repeated cycle of instructions provided that a few of these instructions can be modified slightly at each passage through the cycle. Thus to form the sum of a series of n numbers held in the store, the sequence of instructions must carry out the following operations :

Set total to zero

→Pick up x_i from store ($i = 1, 2, \ldots, n$)
add x_i to total
test for end of series
No Yes

Finish

At each passage through this cycle the "pick-up" instruction must refer to a different number in the store. An ingenious device enables the modification to be combined with a count which also provides the basis for the final discrimination. The numbers x_i are held in locations in the store which are numbered consecutively, and the "pick-up" order is so written as to refer to the first of these locations. Before it is actually obeyed, however, a count number i (starting at n) is automatically added to it in such a way as to make it refer to the ith location. At the end of each cycle, the count is reduced by one and then inspected to see whether it has reached zero; this provides the necessary discrimination, which enables the machine to leave this part of the computation and to proceed to the next.

Certain sequences of instructions are likely to be required in several different places during the course of a complete programme —for example, those for evaluating square-roots and for organizing the input and output of information. Such a sequence of instructions is known as a *sub-routine*; a sub-routine, once written, can be incorporated in any programme without the programmer having to investigate its detailed mode of operation. The usual technique is to supply the sub-routine, whenever it is entered, with a "link" instruction, which in the simplest case is merely the first instruction that is to be obeyed after the sub-routine has finished its task. This "link" is automatically stored by the sub-routine itself and ultimately referred to in order to get back into the main programme.

The N.R.D.C.–Elliott 401 Computer

The computer used in the Statistics Department has been described elsewhere (Lipton, 1955). In brief, it is a binary machine (working in the scale of 2 rather than the scale of 10 used in ordinary arithmetic) with a store containing 2,944 locations of 32 binary digits each (this is equivalent to between nine and ten decimals, and represents the accuracy to which normal arithmetic is carried out). The store is a magnetically coated disc rotating at over 4,500 r.p.m. The disc is divided into 23 tracks, each with 128 locations. Reading a number from the store takes 0·1 msecs. and this is also the time taken to carry out an addition or subtraction; multiplication takes 3·1 msecs. In addition to the main store, there are five registers, each of 32 binary digits capacity, which have immediate access— a number or instruction in the main store is only accessible once per revolution of the disc, so that in an unlucky case up to 12·8 msecs. may be wasted in waiting for the required store-location to arrive at the reading–writing station. For this reason, consecutive instructions are not placed in adjacent locations in the store, but are spread out at the will of the programmer so that, as far as possible, each order becomes available for reading as soon as the previous order has been completed. To enable this to be done, each instruction specifies the location from which the next instruction is to be drawn.

Input to the machine is by 5-hole teleprinter punched tape. This is read by a tape-reader capable of operation at up to 200 rows per second, which is comparable with the computing speed of the machine. Very recently, a punched-card input has been added. Output is either to an electric typewriter operating at 8 characters per second or to a tape-punch, which is about three times as fast; output tape can be printed out on standard teleprinter equipment away from the machine.

The arithmetic and control units of the machine are built up of some 250 plug-in units of about a dozen different types. These carry out logical operations, and the arithmetical operations are built up by connections between the plates. This packaged construction is of immense help in the day-to-day maintenance of the machine and in the tracing of faults.

Programming and coding

The first step in organizing a piece of computation for the machine is to decide on the numerical methods to be employed. These may be quite different from those which would be adopted if the same problem was to be tackled on a desk machine. A good human computer is capable of taking advantage of peculiarities in the data, and of taking special action to retain accuracy at awkward places, but he is easily bored and inevitably subject to error in copying out intermediate results. The machine, on the other hand, will happily allow rounding off and cancellation errors to swamp its results, unless the programmer has taken steps to prevent this, but will carry out repetitive tasks rapidly and accurately.

The arithmetic process has next to be broken down into a number of logical steps, each of which can conveniently be considered in isolation. This is particularly important with a complex programme through which the machine may have to steer several different paths according to the precise nature of the data. Frequently, different parts of a large programme may perform practically identical operations on different intermediate results. These can conveniently be programmed as formal sub-routines.

The final stage consists in writing the actual instructions which enable the machine to perform the required operations. On the Rothamsted computer, each instruction specifies first a source of information, which may be the store or an immediate access register; next a function, which specifies the way in which the number from the source is to be combined with the contents of a special register called the accumulator; and next the destination to which the result of the previous instruction is to be sent. A further number is used to indicate discrimination or order modification as described earlier.

In addition, there is a timing number (in the form of a store address) which specifies the moment at which the order is to be obeyed; if the order contains a reference to the store, this timing address will specify the actual location required. Finally, the order contains the address in which the next instruction to be obeyed can be found. As an example, an order might read

1·52 6030 1·30

1·52, location 52 on track 1, is the address of the next order. Source 6 is the main store; the number from location 1·30 is to be added (function 0) into the accumulator, whose previous contents are to be sent to destination 3, one of the immediate access registers.

This " machine language ", though fairly complex, is sufficiently logical to be quickly mastered, and once the necessary arithmetic has been decided upon, the process of writing the appropriate orders is straightforward, if time-consuming. In practice, the logical section of the orders is written first, the addresses being filled in afterwards.

Statistical uses of the computer

The jobs handled by the computer fall into two main categories—routine tasks which, although individually simple, arise in sufficient volume to justify the writing of programmes, and more elaborate work which is too complex or time-consuming to be a practical proposition on desk machines.

In the first category the most important class of work is the analysis of the results of field experiments. These are readily handled by human computers—a fact which has contributed largely to the development of modern statistical methods in experimentation—but the volume of work involved has become considerable in recent years. Programmes are available for analysing randomized blocks (up to 126 plots), Latin squares (up to 10×10), randomized blocks with split plots (up to 128 sub-plots), 3^3 single-replicate factorial experiments and 2^n factorial experiments, which together account for some 80 per cent of all experiments reaching the department; other programmes are being developed. As an example of the speed of operation the actual analysis of a single variate takes about 15–30 seconds; input and output bring the total time up to about 2 minutes. Using these programmes, experiments involving a total of 2,500 analyses have been handled over the past two years.

A very important feature of these programmes is that they do all the work involved in an analysis. To begin with, the figures actually received from the field are very seldom those that are to be analysed; at least some conversion, say from lb./plot to cwt./acre, will be required, and often more elaborate initial computation will be called for. We use a general input routine for experimental designs which takes care of all this preliminary data-handling, places the required figures in the correct locations in the store and carries out certain checks to guard against punching errors. On the output side, the programmes are arranged to print their results in the customary form, leaving the minimum of clerical work to be done before the results can be dispatched to the experimenter.

Another source of routine work is probit analysis, which arises in insecticide research and other fields. Statistically, the problem is one of weighted regression, and the computations, though straightforward, are laborious and time-consuming. One of our programmes fits a single probit line to up to 16 observed points, printing out the equation to the probit line, the ED50 and its fiducial limits; natural mortality and heterogeneity in the data can be allowed for, and the same programme can without modification use the logit or angular transformations in place of probits. A further programme fits a bivariate probit regression, or probit plane. This useful technique has hitherto been neglected in practice because of the tedium of the computations involved.

Intermediate between the routine tasks and the large-scale computational problems are the programmes dealing with multiple regression. The first stage in regression calculations is the computation of sums of squares and products, and this can easily outweigh the more sophisticated calculations that follow it. We have several programmes for this purpose that can at will provide weighted or unweighted means, sums of squares and products, variances and covariances, standard deviations and correlation coefficients. These will shortly be adapted to punched-card input, since much multivariate material is most easily made available on punched cards.

The next step in multiple-regression calculations involves the inversion of a matrix and the calculation from the inverse of the regression coefficients and their standard errors. One programme will handle up to 24 variables, and inverts a 10×10 matrix in about 8 minutes. Another, given the sums of squares and products of up to 35 variables, enables the operator to select any one of these as a dependent variable and any selection of up to 9 others as independent variates. At each stage, the operator can add a new independent variate to his regression equation, replace the last independent variate added by a different one or delete one of the earlier independent variates. In each case, the machine will recalculate the regression and print out the residual mean square with its degrees of freedom and the regression coefficients with their standard errors.

Other programmes, which, though scarcely in routine use, are general in their application, have been devised to handle various matrix operations. As an example, one programme will evaluate all the latent roots and vectors of a symmetric matrix, an 8×8 matrix taking about 5 minutes. This problem arises in general discriminant analysis and has been used in a recent study by this technique of the teeth of fossil anthropoids.

A number of special problems involving heavy computations have been tackled on the computer, and some of these may be briefly mentioned. A large body of data from the Danish pig progeny testing stations is being analysed for Dr. J. W. B. King (Animal Breeding Research Organization, Edinburgh). Several different measurements are taken on each pig, and it is required to break down the observed variances and covariances into genetically meaningful components. The estimation of linkage values from human pedigree data is being undertaken for Dr. J. H. Renwick (Galton Laboratory).

It has been suggested that tsetse flies could be eradicated from an area by the release of large numbers of sterilized male flies. Practically nothing was known, however, about the numbers of flies which would be required, or about the length of time over which release should be continued. By setting up a mathematical model of the tsetse population and following it through many generations on the computer, both these points were investigated.

The feeding of dairy cattle is regulated on an empirical basis, and it is likely that the full efficiency of the cow is not being realized. K. L. Blaxter and H. Ruben (Hannah Dairy Research Institute) have approached this problem by setting up a rather elaborate mathematical model of the cow's metabolism. Fitting this model to observed data is an extremely arduous task, and is now being programmed for the computer.

There are many numerical problems which, although simple in themselves, are too time-consuming to be practical on desk machines. A typical example is the estimation of sampling errors for different patterns of sampling from completely known material. We have programmed this problem for the simple case when the sampling units form a linear sequence in space or time. The programme has been applied to data on human dietary constituents.

An obvious application of the computer is to the construction of mathematical tables, and several of the new tables in the fifth edition of *Statistical tables for biological, agricultural and medical research* were computed in this way. A large-scale project was the computation of tables of a generalized Beta distribution in collaboration with G. Foster (London School of Economics).

It may have been realized that the main difficulty in employing an electronic computer lies in the writing of programmes. The general outlines of the code of instructions for the 401 machine have been given above, and it will have been seen that programming is complicated by the "optimum access" feature—each instruction has to carry the address of the next instruction to be obeyed, and the relative placing of the instructions can have a large effect on the speed with which a programme will be carried out. In addition to this the relations to each other and to the location in which the instruction is stored of the two locations mentioned in each instruction (the timing address and the address of the next instruction) sometimes form part of the logical content of the instruction. For this reason, there are various conditions on the parities of the various locations that have to be borne in mind, and also certain delays which, if not imposed by the programmer, will cause the machine to "waste a revolution" or occasionally to perform the wrong operation. These conditions are straightforward but rather numerous, and form a potent source of errors when a programme is being written. To meet this problem, we have developed an automatic programming routine which enables this part of the programming load to be borne by the computer itself; the programmer uses a simplified coding to express the logical and arithmetic content of his instructions, and the routine fills the appropriate timing, at the same time indicating possible inconsistencies that it has detected in the simplified code. A register of occupied store locations is printed out, and an order tape punched ready to feed into the machine.

This routine has been found to produce programmes whose timing is as good as or better than the average human programmer and which contain far fewer errors when they are tested for the first time.

A field of application which we propose to develop in the immediate future is the application of the computer to sample-survey analysis. Apart from its speed of operation, there are several points at which the computer is expected to contribute. To begin with, any large batch of numerical data almost inevitably contains a few gross errors. These can have a disproportionate effect on the results, especially on estimates of error; yet their discovery and elimination is usually beyond the capacity of the unaided human investigator. We have made some progress using standard punched-card equipment, but much work remains to be done. A second task for which the computer is well suited is the preliminary computation of indices and other quantities on which the actual analysis will be carried out. Then, the data on one sampling unit may specify that x tons of some mixed fertilizer was applied to a field of y acres; what is required is the amounts of N, P and K applied, in cwt./acre. The full utilization of this stage will require machinery for punching from tape on to cards. Lastly, electronic computation should lead to improvements in the summary tables of results and to greater efficiency in the methods of collecting information, since the fact that some analytical technique requires elaborate numerical work need no longer be a barrier to its use.

References

Lipton, S. (1955). A note on the electronic computer at Rothamsted. *Math. Tab., Wash.* **9**, 69.