A Modern Approach to Highway Materials Sampling

Techniques modernes d'échantillonnage pour travaux routiers

B. A. KANTEY, *Consulting Engineer, Cape Town, South Africa*
R. K. MORSE, *Foundation Engineer, El Paso, Ill., U.S.A.*

SUMMARY

Highway engineering, particularly in developing countries with inadequate staff, can benefit considerably by making full use of all available techniques. Two such techniques, air-photo interpretation applied to highway materials and statistical control of sampling and testing, have been used with success in South Africa. The authors describe the basic principles involved in the adoption of these tools and quote some examples to indicate the benefits that can be derived.

SOMMAIRE

Dans les pays en expansion qui souffrent d'une pénurie de personnel, le génie routier peut et doit bénéficier de toutes les nouvelles techniques. Deux de ces techniques: l'interprétation de la photographie aérienne et le contrôle statistique de l'échantillonnage et des travaux d'essai, sont employés avec succès en Afrique du Sud. Les auteurs décrivent les principes fondamentaux impliqués dans l'adoption de ces techniques et ils citent quelques exemples pour montrer leurs avantages.

MODERN HIGHWAY ENGINEERING requires, *inter alia*, a thorough knowledge both of the *in-situ* materials to be traversed by the highway and of those materials which may be incorporated into the road. Usually this knowledge is acquired by a programme of interval sampling along the centre line, supplemented by off–centre-line prospecting for borrow materials. With recent advances in air-photo interpretation, soil mapping has taken an increasing part in the materials survey and, in South Africa, new applications of this tool are being used with increasing confidence (Brink and Williams, 1964).

The South African approach is characterized by the soil engineering map. This is not an adaptation of a map drawn for other purposes but is an engineering map delineating soil map units of engineering significance. It pictures the complete soil profile, based on concepts developed by Brink and Jennings (1961) and Kantey and Williams (1962), and it emphasizes the engineering characteristics of each soil horizon. It is very common to find that one horizon in the soil profile is of particular importance to the materials engineer. The term soil unit has been introduced to define an individual horizon of a soil map unit. It is commonly accepted today that soils do not occur haphazardly but are formed by logical natural processes, and that a similar set of natural processes, acting on a similar parent material, will produce a similar soil profile.

SOIL ENGINEERING MAPS

In the production of soil engineering maps, areas having soil profiles with similar characteristics are delineated by studying the effects of these natural processes on the parent geology. Hence, within the accepted variation in test results, the test data from one area should be similar to those from other areas having the same soil units. These mapping units are delineated by air-photo interpretation. To make the most efficient use of this new tool, selection of the soil units should be based primarily on those engineering properties which are used to design the road. The sampling and testing programme should concentrate on the soil units that are most variable or on those that have an engineering property near the rejection limit in the specification. Under the interval sampling method, the materials engineer, in any case, eventually groups those soils having similar descriptions and then evaluates the pertinent physical properties of each group.

Once it has been established that a soil engineering map adequately delineates the various significant materials, it is no longer necessary to restrict sampling locations to the roadway. Planned sampling within any area encompassed by a soil unit might be expected to define that soil unit as well as would sampling along the centre line. It is also logical that efficient use of this tool should be made at a very early stage in highway planning, preferably before the choice of location has been finally decided.

The grouping of soils and the evaluation of properties of the soils so grouped may not warrant an elaborate procedure when the soil survey covers only a small area. When a large area is involved, or when a small area is being intensively evaluated, the quantity of data that is necessary and the cost of obtaining it, can justify considerable precision in selecting the number and location of samplings and tests. Even greater economies would be possible in those locations where the roadway is inaccessible but where the soil units along the centre line extend into areas in which sampling is more practicable. In many developing countries this would permit very significant economies.

STATISTICAL APPROACH

If it is intended to characterize the soil units by any method other than interval sampling along the centre line, there should be some way of verifying the uniformity of each soil unit wherever it is being sampled. This results in a statistical approach to the interpretation of the results. Much pioneering work on the application of statistics to soils has been carried out at the University of Illinois by Morse and Thorburn (1961), Morse (1961), Liu and Thorburn (in press), and Thorburn, Morse, and Liu (in press) on agricultural soil maps. An opportunity presented itself in South West Africa, on a particular road project, to ally this work previously carried out on the reliability of agricultural soil types to the South African concept of engineering soil mapping and its soil units. The sampling and testing programmes were based on a system of statistical controls.

As usual, there was a specified rejection limit (μ_0) for each of several soil properties. For the foundations of a bridge pier, any test value falling beyond the rejection limit must be considered very carefully. In the case of a highway subgrade, a single failure would not be considered as catastrophic. In addition, during construction of the subgrade, the soils are usually mixed and remoulded, and inspection and control are possible at most stages. Under these conditions, rejection because of an occasional unsatisfactory test value would result in an unjustified increase in cost. Since approximately half of the material to be used will be of poorer quality than is represented by the mean, statistical methods that have been used for evaluating soil units in terms of mean test values furnish results that are not directly usable in making design decisions.

In order to use a more appropriate precision in the rejection procedure, a statistical method was devised to estimate the proportion of the population that would fall beyond the rejection limit, the population being all the soil samples that could possibly be taken from the soil unit. This estimate is based on the assumption that the variability of a particular measurement will have a normal distribution; an assumption that should be reasonably reliable if the soil units are properly chosen. It is also assumed that the soil samples will be chosen in a random manner.

STATISTICAL THEORY

If a distribution is normal, there is a probability of 0.80 that test results would fall within the range bounded by the population mean ± 1.28 times the population standard deviation ($\mu \pm 1.28\sigma$). In other words, when random soil samples are selected, one would expect 80 per cent to fall within the range $\mu \pm 1.28\sigma$. Similarly, 10 per cent might fall above this range and 10 per cent below the range. Since a soil specification generally has either a maximum or a minimum specified value, we are interested in estimating the proportion of the population that lies either above or below this specified value. For example, the probability would be 0.90 that measurements of an engineering property would be less than $\mu + 1.28\sigma$. The probability would be 0.95 that these test results would be less than $\mu + 1.64\sigma$. Similarly, other probabilities can be estimated from the area that lies under the equation of the normal curve.

To make these relationships useful in a typical soil survey, the size of the statistical sample, in other words the number of individual soil samples (N), must be taken into account. Because of the infinite number of possible test samples, the standard deviation of the population (σ) cannot be determined. However, the standard deviation of the sample (s) can be calculated from the test data and used as an estimator of σ. Where the number of samples is large, s approaches σ and can be substituted for it in the calculations. If less than about 30 test results are available, it is more appropriate to use the t distribution. The value of t can be determined from a statistical table giving the distribution of t (Snedecor, 1956). To determine t from such a table only the number of samples and the probability need be known. For ten samples and a probability of 0.90 a value of 1.38 is obtained for t*. The value of t becomes 1.83 if a probability of 0.95 is selected. When the t distribution for ten samples is used, the range of $\mu \pm 1.28\sigma$ becomes $\mu \pm 1.38s$ and the probability is 0.90 that the population will have test values less than $\mu + 1.38s$.

Similarly, the population mean (μ) can never be determined. For a statistical sample of considerable size, one might use the sample mean $\bar{x}$ as an adequate estimator. However, a soil engineer must usually rely on such a small-sized sample that a considerable error could be introduced by using $\bar{x}$. The deviation of the sample mean from the population mean cannot be determined, but the distribution of this deviation is known. The standard error of the mean ($S\bar{x}$) is the standard deviation of this distribution. Consequently, the probability is 0.90 that the deviation ($\mu - \bar{x}$) will not exceed 1.38 $S\bar{x}$ if 10 test results have been used in the calculations.

With a probability of 0.90 that the measurement of an engineering property will be less than $\bar{x} + 1.38s$, and with a probability of 0.90 also, that ($\mu - \bar{x}$) will be less than 1.38 $S\bar{x}$, it is possible to arrive at an over-all probability. The standard error varies directly with the standard deviation. This results in a probability of 0.90 that a measurement of the population will not exceed $\bar{x} + 1.38s + 1.38\ S\bar{x}$. Similarly, the probability is 0.95 that $\bar{x} + 1.83s + 1.83\ S\bar{x}$ will not be exceeded. If this latter value does not exceed the specified rejection limit, one would predict that at least 19 out of 20 samples would pass the specification.

To determine the probability that the specification will be met by a particular population, this value can be equated to the rejection limit with t as an unknown quantity: $\mu_0 = \bar{x} + ts + tS\ \bar{x}$. The value of t can then be interpolated in a t table to obtain the appropriate probability. By this method all the results of a particular test on a soil unit are combined into a single number that indicates the proportion of the samples from a soil unit that will pass the specification. This is probably the most useful form for presenting test data to the designer.

PRACTICAL APPLICATION

This should make it possible to set up a much more efficient programme during both the sampling and testing stages. It is wasteful to process a great many samples from a soil unit that is reasonably uniform or that is well within a specification. At the same time, to evaluate a highly variable soil unit, or one with properties near the rejection limit, may require so many samples that even the typical interval sampling programme is not sufficiently conservative. Actually, the process of highway construction in which material is removed from a borrow pit and placed in the highway, automatically results in a considerable mixing of the material. This reduces its inherent variability. The possibility of processing a material to improve its properties from outside a specification to within the specified limits must also be borne in mind by the materials engineer. Each of these factors is more readily assessed if a statistical approach is used.

While any probability can be selected as the criterion for meeting a specification, it is felt that 0.90 is likely to be most appropriate for highway work. For structural foundations or for slope stability problems, where failure is likely to be more serious, a higher probability is needed.

PRACTICAL EXAMPLE

In applying these principles to the project in South West Africa, it was decided to check the reliability of off–centre-line sampling. Where centre-line soil units were concerned, sampling and testing was carried out at approximately one-

---

*If a "one-tailed" table is used, the value of t can be found in the column headed by the probability actually used. If a "two-tailed" table is used, the value of t for a 0.90 probability will be found in the column corresponding to a 0.80 probability.

mile intervals along the centre line, at approximately one-mile intervals a quarter mile alternately left or right of centre line, and at rather closely spaced intervals in a randomly chosen type area. If the soil unit occupied a large area, additional type areas were sampled and tested as additional checks. The results of these tests were analyzed statistically, first by treating each group of samples separately and then by analyzing all samples from the soil unit.

It became apparent that the soil units could be conveniently grouped into three basic classifications: (1) soils formed from parent rock by decomposition *in situ*; (2) soils formed from transported materials; (3) pedogenic soils. Each of these groups presents the materials engineer with problems and with opportunities peculiar to itself. In general, soils formed by *in-situ* decomposition proved to be comparatively uniform, while transported soils—mostly alluvial—proved to be rather variable. Pedogenic soils may be either uniform or variable, but are often of very great importance as a source of aggregate or of material for selected layers in construction.

TABLE I. PROPERTIES OF PLASTIC BOULDER SHALE

	Centre line	Off centre line	All samples	Type area "A"	Type area "B"	Type area "C"
Number of samples	18	16	71	14	11	12
Mean w_L	22.2	21.6	21.4	22.8	19.8	19.6
Standard deviation	4.67	2.90	4.38	2.86	1.78	1.88
90 per cent probability	29.9	26.5	27.8	27.7	23.0	23.0
Percentage probability to meet specification	>97.5	>97.5	>97.5	>97.5	>97.5	>97.5
Mean I_P	9.8	10.0	9.8	10.2	9.1	9.8
Standard deviation	2.14	1.86	1.81	1.93	1.76	1.11
90 per cent probability	13.3	13.1	12.4	13.5	12.3	11.7
Percentage probability to meet specification	83.0	79.1	85.8	74.9	89.6	93.8

TABLE II. PROPERTIES OF TERRACE GRAVELS

	Centre line	Off centre line	All samples	Type area "D"	Type area "E"	Type area "F"	Type area "G"
Number of samples	12	9	91	18	12	18	22
Mean w_L	21.0	22.6	21.6	22.4	19.4	22.1	21.3
Standard deviation	2.98	3.54	4.02	5.64	1.73	3.64	4.25
90 per cent probability	26.2	29.2	27.4	31.7	22.4	28.1	28.1
Percentage probability to meet specification	>97.5	>97.5	>97.5	>96.8	>97.5	>97.5	>97.5
Mean I_P	9.5	10.6	10.5	11.8	9.7	10.1	10.5
Standard deviation	1.88	2.07	2.54	3.28	1.37	1.84	3.33
90 per cent probability	12.8	14.4	14.2	17.2	12.1	13.1	15.8
Percentage probability to meet specification	84.3	67.5	68.6	51.8	90.0	78.3	63.2

Tables I and II give results of the analysis for two major soil units. The plastic boulder shale is a residual soil, while the terrace gravel has been transported. In each case the A and C horizons are not significant, and only the B horizon was tested. It can be seen immediately that the plastic boulder shale is relatively uniform and that either the centre-line or off–centre-line tests would have defined this material adequately. This particular soil unit covered a length of 26 miles on centre line. Common practice in South Africa is to sample and test at a spacing of five to ten points per mile. Normally this would have resulted in the sampling and testing of 130 to 260 samples. It is considered that 16 to 18 samples from off centre line or centre line defined this material adequately, a saving of considerable importance.

The terrace gravels, on the other hand, are quite variable. The unit covered about five miles on or near centre line and it is doubtful whether the 25 to 50 samples taken under standard practice would have characterized this soil adequately. Statistical parameters indicated that this unit consisted of variable material. This, in turn, led to a critical inspection of the pattern of test results from the type areas, from which it was found that minor areas of less variable and very useful construction material could be isolated.

FUTURE DEVELOPMENTS

The preparation of a soils engineering map usually involves an initial examination of the air photos resulting in the preparation of an approximate map. This map is then checked in the field and usually a considerable refinement of soil units will be indicated. An initial sampling and testing programme, of perhaps ten samples, can tentatively evaluate each of the soil units. Soil units showing high variability or troublesome characteristics may require additional sampling and testing. In searching for suitable borrow or selected material, additional samplings can be concentrated in those areas where better test results were obtained. These samplings may indicate a sub-area where the material is of better quality or of lesser variability. With this information available, if necessary, a final programme of conventional borrow pit sampling can be carried out.

In applying these techniques, the expansion of soil engineering mapping from a narrow strip to the coverage of a rather wide area, together with the initial sampling and testing programme, involves comparatively little additional cost. Sampling and testing could be carried out at speed in chosen areas of easier accessibility. This would be especially advantageous in countries with high seasonal rainfall and it would permit the maximum amount of design information to be obtained with minimum staff and at minimum cost. It will also offer locational economies by making available basic soils information, covering a wide area, at an early stage of planning.

The soil engineering map and the test data can be very useful in many types of planning decisions. Decisions on industrial plant location and regional planning and zoning, for example, may be made on a much sounder basis when soil maps are available.

REFERENCES

BRINK, A. B. A., and J. E. B. JENNINGS (1961). Soil profiling in civil engineering. *Civil Engineer in South Africa,* Vol. 3, pp. 145–51.

BRINK, A. B. A., and A. A. B. WILLIAMS (1964). *Bulletin on soils engineering mapping on roads in South Africa.* National Institute for Road Research, C.S.I.R., Pretoria.

KANTEY, B. A., and A. A. B. WILLIAMS (1961). The use of soil engineering maps for road projects. *Civil Engineer in South Africa,* Vol. 4, pp. 149–59.

LIU, T. K., and T. H. THORBURN (in press). *An engineering study of statistical variations in a group (Humic-Gley) of surficial soils in Illinois.* University of Illinois.

MORSE, R. K. (1961). Engineering properties of the surficial soils of Livingston County, Illinois. Ph.D. thesis, University of Illinois.

MORSE, R. K., and T. H. THORBURN (1961). Reliability of soil map units. *Proc. Fifth International Conference on Soil Mechanics and Foundation Engineering,* Vol. 1, pp. 259–62.

SNEDECOR, G. W. (1956). *Statistical methods.* Fifth edition. Iowa State College Press.

THORBURN, T. H., R. K. MORSE, and T. K. LIU (in press). *Engineering soil report, Livingston County, Illinois.* University of Illinois.