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Simple Overlay Design Method for Gravel Roads

ABDULLAH HOMSI

A simple method to use deflection measurements for design of overlay thickness on low-volume gravel roads is described. Deflection values are recorded at the center of a circular loading plate and at a certain distance from the center. By using the theory of elasticity, it has been found that a certain arithmetic function of the two deflections measured varies almost linearly with the subgrade modulus within rather wide limits of thickness and elastic modulus of the gravel layer; the relation is nearly independent of these values. This relation has been confirmed by analysis of a large number of measurements made by the falling-weight deflectometer on a number of gravel road sections. Similarly, a relation for determination of the upper layer thickness in a two-layer system has been found. Determination of the design deflection meets with two problems: variation along the road and variation with season. The effect of variation along the road will be solved by using running averages and that of seasonal variations by applying a weighting factor. For simplification of the design procedure, it has been assumed that there is a constant ratio between the subgrade modulus and the modulus of the gravel layer; this assumption has been confirmed by actual measurements. Analysis of the standard designs prescribed by the Swedish Road Specifications on different subgrades at different traffic intensities has shown a unique relation between vertical subgrade stress and traffic intensity at each subgrade type. The required equivalent overlay thickness may therefore easily be selected and the corresponding overlay thickness of different paving materials determined. A discussion follows regarding the practical problems associated with the measurement procedure, such as length of intervals between measurements, magnitude of load applied, nonlinearity of materials, and seasonal variations.

The purpose of this study is to present a simple evaluation procedure for the bearing-capacity assessment of gravel roads and an overlay design method.

The study is based on numerical values obtained from the computer program BISAR (1) for the calculation of stresses, strains, and deformation in multilayer systems according to the theory of elasticity. Trends of the deformation behavior have been studied rather than absolute values, in order to avoid the unrealistic results that may emerge from such programs, especially when applied to values from dynamic [falling-weight deflectometer (FWD)] tests.

The study is divided into three main parts:

1. The design method, which is based on the relations obtained from the theory of elasticity and tested against actual measurements performed on sections with known subgrades, gravel thickness, and frost susceptibility;
2. Discussion of the design parameters, i.e., the E-moduli, the allowable stress, and the justification for the use of the stress in the subgrade as design criterion; and
3. Treatment of some practical problems associated with the measurement procedure and summary of the whole method as it would be used in practice.

DESIGN METHOD

The thickness design method had to satisfy two main requirements: first, to comply with the current design practice in Sweden, i.e., with the Swedish Design Specifications [Byggnadstekniska Anvisningar (BYA)] (2); second, to use the two deformation values resulting from deflection measurements at the loading plate center and at a certain distance from that center (e.g., those that use the FWD). Those two deformation values should reflect the bearing capacity of the subgrade and the existing thickness of gravel on top of it. In order to fulfill the first requirement, the standard designs of BYA were analyzed by means of the BISAR program; a load of 50 000 N was assumed to be applied to a plate of 15-cm radius (loading conditions typical for FWD).

The values obtained for the allowable stresses calculated from BYA were plotted against the average traffic flow in every traffic class, and the results are shown in Figure 1. By extrapolation to the traffic flow of 500 vehicles/day, the allowable stresses for each of the subgrade types were obtained for this traffic flow.

In order to find a useful indication of the subgrade bearing capacity, a study has been performed of subgrades that have a variation of bearing capacity from $E_u = 15$ MPa to $E_u = 100$ MPa; different moduli of the upper layer are assumed and again each has a thickness variation from 10 to 100 cm. The two surface deformations D_0 and D_x at the plate center and 450 mm from the center corresponding to every subgrade, gravel modulus, and thickness combination were obtained by the aid of the BISAR program. Table 1 represents a typical example from the study.

Many arithmetical combinations of the surface deformation values were studied (not shown in Table 1) and plotted against the E-modulus of the subgrade and the thickness of the upper layer. The expression $V = (1/D_x) - (1/D_0)$ has been found to be a useful indication of the bearing capacity of the subgrade. Figure 2 shows the linear relation $(1/D_x) - (1/D_0)$ against E_u and its relation to the modulus of the upper layer and its thickness. The scatter lines shown correspond to the thickness range of 10-70 cm, which is seldom exceeded in gravel roads.

Figure 3 illustrates the relation between $(1/D_x) - (1/D_0)$ and h. Each group shown belongs to one subgrade modulus, and the variation within each group is a result of the gravel modulus variation. Actual field variation would be less than that shown in Figure 3, since the ratio E_1/E_u would vary within the range $E_1/E_u = 2-4$ in most cases (3).

The next step was to find an indicator of the thickness of the upper layer. The deformation at the loading center (D_0) was found convenient for this purpose. Figure 4 shows the relation among the three variables $(1/D_x) - (1/D_0)$, D_0, and h for the E_1/E_u ratio proposed by Heukelom and Klomp (3) ($E_1/E_u = 0.586^{0.457}$).

Figure 1. Allowable subgrade stress derived from BYA specifications for subgrades A-E.

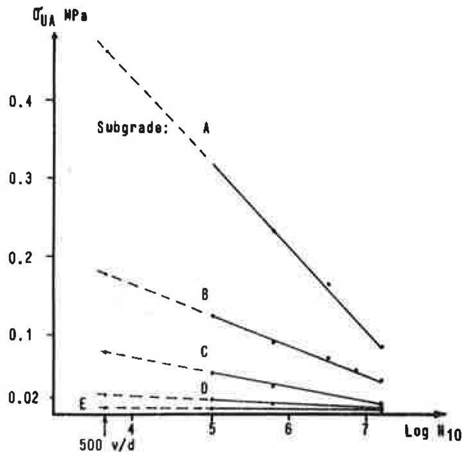
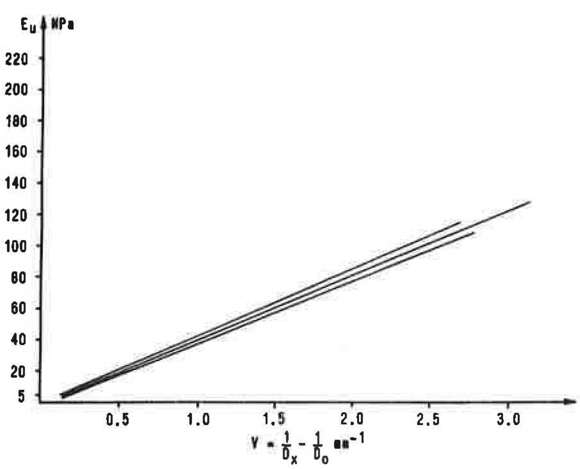


Figure 2. Relation between V and E_u at different thicknesses and modulus ratios E_1/E_u calculated by BISAR program.



In order to compare this result with field measurements, about 150 sections were studied. The subgrade type, thickness of the gravel layer, and frost susceptibility were known. Deflection measurements had been performed, two in the frost pe-

Figure 3. Relation between V and h calculated by BISAR program when different values of E_u and E_1/E_u are assumed.

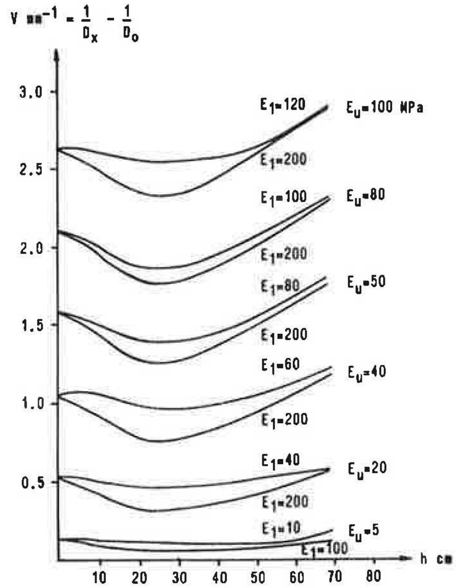


Figure 4. Relation between V and D_0 when different values of gravel thickness (h) calculated by BISAR program are assumed.

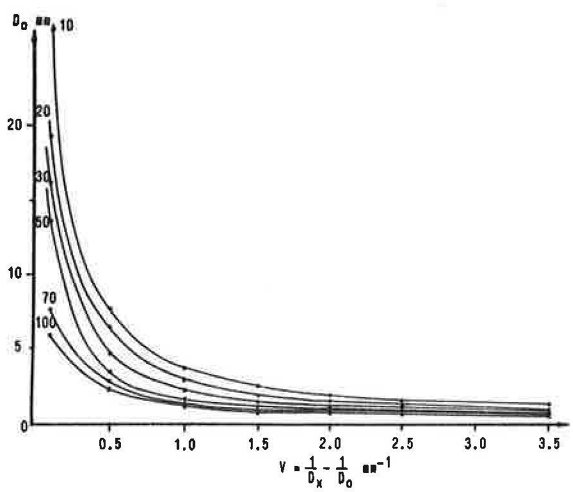


Table 1. Typical data sheet from deformation study.

E_u (MPa)	E_1 (MPa)	h (cm)	D_0 (mm)	D (mm)	D_x/D_0	$D_0 - D_{450}$ (mm)	σ_u (MPa)	V mm^{-1}
20	120	10	6.032	1.609	0.2667	4.423	0.413 96	0.455 72
		20	4.159	1.632	0.3924	2.527	0.187 21	0.372 30
		30	3.352	1.493	0.4454	1.359	0.101 1	0.371 46
		50	2.652	1.191	0.4491	1.461	0.412 4	0.462 56
		70	2.342	0.982	0.4193	1.360	0.218 7	0.591 34
		100	2.107	0.791	0.3754	1.316	0.109 5	0.789 61
20	140	10	5.831	1.617	0.2773	4.214	0.394 7	0.446 23
		20	3.931	1.629	0.4144	2.302	0.174 2	0.359 49
		30	3.122	1.472	0.4715	1.650	0.933 9	0.359 04
		50	2.425	1.156	0.4767	1.269	0.379 3	0.452 68
		70	2.116	0.944	0.4461	1.172	0.020 0	0.586 73
		100	1.882	0.752	0.3990	1.130	0.010 0	0.798 44

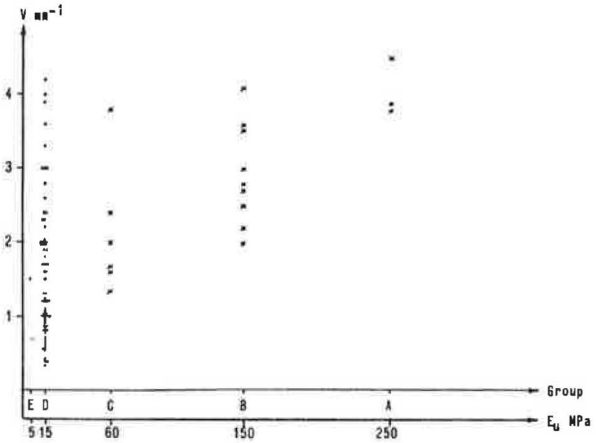
riod and one in the summer and fall periods, on every section (4).

The subgrades of those sections were classified according to the Swedish practice into five groups--A, B, C, D, and E. The moduli of those groups are not accurately known. Values suggested by Broms and by Ringström are shown in the table below (2,5):

Source	Modulus (MPa) A	B	C	D	E
Ringström	200	80	40	15	3
Broms	250	150	60	15	5

The values $(1/D_x) - (1/D_0)$ pertaining to all the sections were computed from all the measurements performed on that section (frost, summer, and fall periods). The result is plotted against the subgrade modulus in Figure 5, in which each section is represented by three points and the subgrade classes are spaced according to the values suggested by Broms.

Figure 5. Measured values of V on roads on different subgrades (A-E).



Although the scatter is large, as may be expected, the value of $(1/D_x) - (1/D_0)$ for the subgrade type D varied around 1 mm^{-1}; the lower limit was 0.4 mm^{-1}, which theoretically corresponds to an E-modulus value of about 15 MPa. This is in good agreement with the value for material D given in the table above.

A further step was to calculate the design E-modulus by applying the season weighting function proposed by Broms (5) and by observing that V $[= (1/D_x) - (1/D_0)]$ is proportional to E_u, which is proportional to CBR:

$$V_m = V_3\left((t_2/12)\cdot\left\{[V_2 - (b/a)]/V_3\right\} + (t_3/12)\right)^{-a/b} = V_3 F_{th} \quad (1)$$

where

V_m = design value of $(1/D_x) - (1/D_0)$,
V_3 = summer-fall value of $(1/D_x) - (1/D_0)$,
V_2 = thaw-period value of $(1/D_x) - (1/D_0)$,
a = 0.16,
b = 0.53 (for unbound top materials),
t_2 = thaw-period duration (months),
t_3 = summer-fall duration (months), and
F_{th} = thaw correction factor.

Figure 6. Thaw factor (F_{th}) plotted against frost-susceptibility classes.

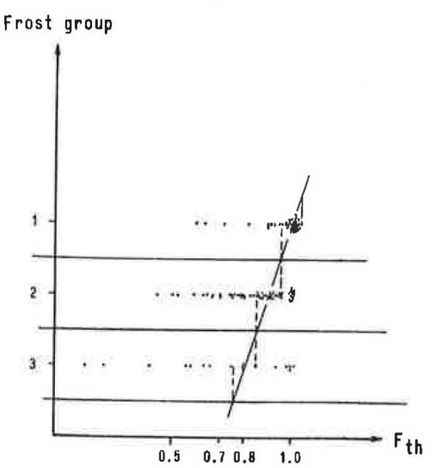
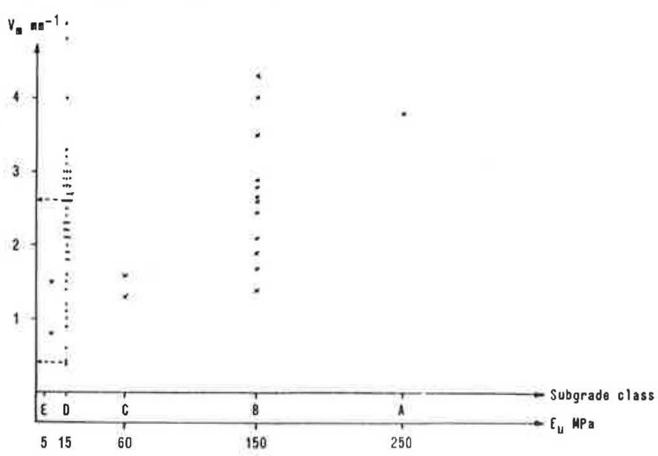


Figure 6 illustrates the relation between the F_{th} factor and the frost-susceptibility grouping followed in Sweden to classify the subgrades. Almost all the subgrades of the 150 sections studied were classified according to this grouping and the factor F_{th} shows a reasonable correlation with this grouping.

In Figure 7 the values of V_m [the design $(1/D_x) - (1/D_0)$] for the subgrade classes A, B, C, D, and E are shown. The lowest value of V_m for the D subgrade is still about 0.4, which corresponds to 15 MPa. The classes are spaced according to subgrade modulus.

Figure 7. V_m plotted against subgrade class.



If we consider D_0 (the deformation at the center) as an indication of the upper-layer thickness, Figure 8 is obtained, which is derived from field measurements only and shows the same trend as the theoretically derived relation in Figure 4. As expected, there is disagreement in the absolute values as a result of the simplifying assumption inherent in the theory of elasticity (friction between layers, loading condition, Poisson's ratio, etc.). Also, the thicknesses are nominal only. The curves displayed in Figure 8 are based on field tests and theoretical considerations.

If we write

$$E_1 = KE_u = Ch^{\alpha} E_u \quad (2)$$

$$h_e = 0.9h\,(E_1/E_u)^{1/3} \quad (3)$$

$$h_e = 0.9C^{1/3}\,h^{1+\alpha/3} \quad (4)$$

and substitute in Odemark's equation (6) as follows:

$$D_0 = (1.5\sigma_0 a/E_u)\left[\left(1 - \left\{1/[1 + n^2(h/a)^2]^{1/2}\right\}\right)(E_u/E_1) + \left\{1/[1 + n^2(h/a)^2(E_1/E_u)^{2/3}]^{1/2}\right\}\right] \quad (5)$$

Figure 8. Relation between V and D_0 according to field measurements.

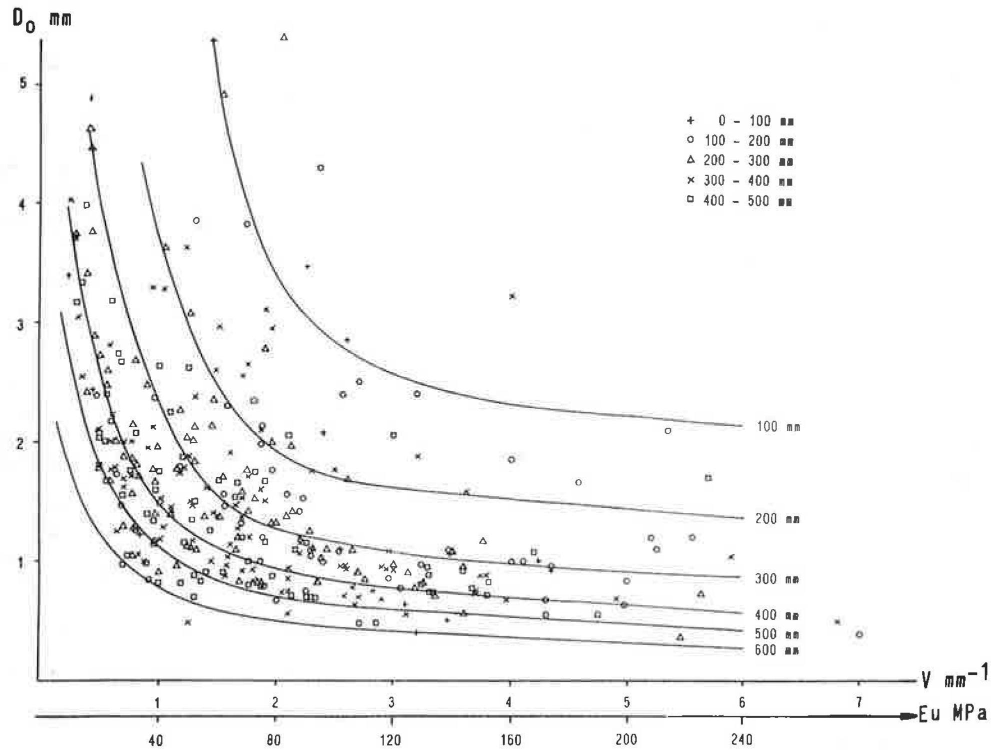
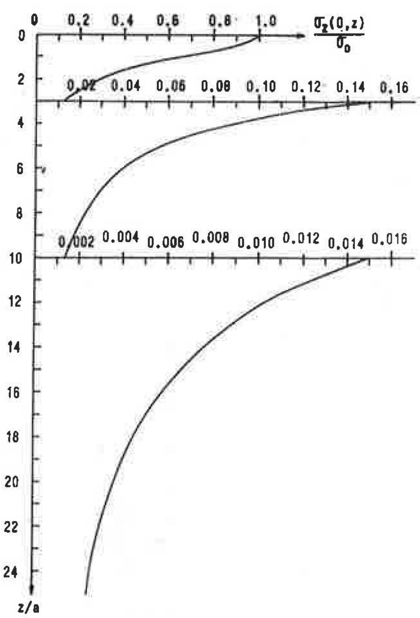


Figure 9. Vertical stress on centerline of load at different depths according to theory of elasticity.



where

σ_0 = load stress on surface,
a = radius of loaded area, and
n = 0.9,

and write

$$E_u = C_1\ [(1/D_x) - (1/D_0)] \tag{6}$$

Odemark's equation will take the following form:

$$D_0 = \left\{1.5\sigma_0\, a/C_1\ [(1/D_x) - (1/D_0)]\right\} \left[\left(1/\left\{1 + 0.81C^{2/3}\ [h^{1+(2/3)\alpha} \div a^2]\right\}^{1/2}\right) + \left(1 - \left\{1/[1 + 0.81\,(h^2/a^2)]^{1/2}\right\}\right)(1/Ch^{\alpha})\right] \tag{7}$$

If we write C = 0.586, α = 0.457 [as suggested by Heukelom and Klomp (3), $E_1/E_u = 0.586h^{0.457}$], the relation $(1/D_x) - (1/D_0)$, D_0, h will yield curves similar to those shown in Figure 8.

In order to use Figure 8 to establish a design chart for gravel roads that carry 500 vehicles/day, the allowable stress was determined from Figure 1. The equivalent thickness for every subgrade class was obtained from the relation between stress and depth shown in Figure 9, derived from the theory of elasticity. The depth read-off in Figure 9 will then be converted to a gravel thickness by using the following equations:

$$h_e = 0.9C^{1/3}\, h^{1+\alpha/3} \tag{8}$$

$$h = (h_e/0.9C^{1/3})^{1+\alpha/3} \tag{9}$$

where C is 0.586 and α is 0.457.

Finally, the needed overlay thickness is the difference between those thicknesses and the thickness given by every curve in Figure 8. The design for a traffic flow of 500 vehicles/day and combinations of $(1/D_x) - (1/D_0)$ is shown in Figure 10. Other diagrams for other traffic flows could be obtained by finding the allowable stresses from Figure 1 and the needed equivalent thicknesses, the needed gravel thickness for every subgrade, and finally the needed overlay thickness corresponding to every combination of $(1/D_x) - (1/D_0)$. The asphalt overlay thickness is then obtained by applying an appropriate conversion factor.

DISCUSSION OF DESIGN PARAMETERS

The design method has been established mainly for roads that are already strengthened with a gravel layer. Figure 11 represents a typical section of such a road. This section was considered as 40-cm gravel on a subgrade of class D. A complete analytical design for such sections is impossible, and simplifying assumptions should be made concerning the nature of the gravel roads and associated cri-

Figure 10. Design chart based on D_0 and V.

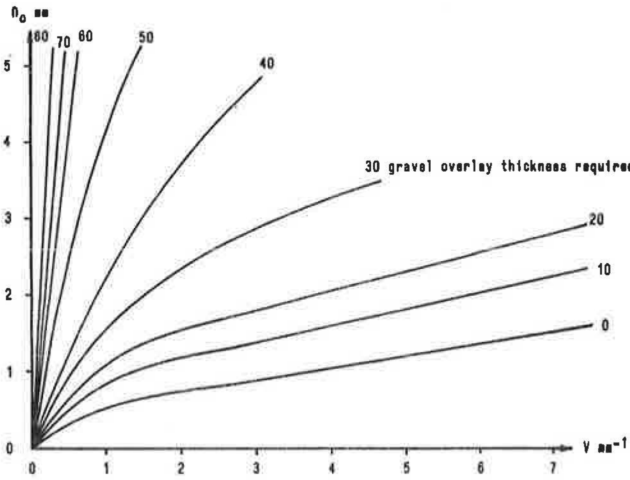


Figure 11. Typical section of roads included in field test (total of 150 sections).

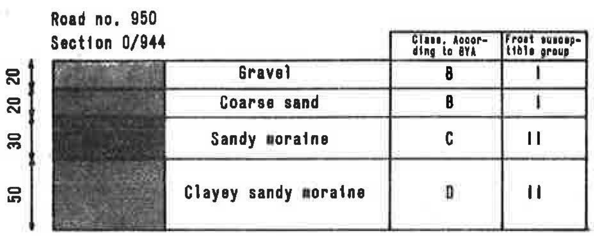
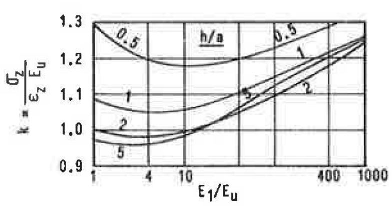


Figure 12. Influence of modulus ratio E_1/E_u on k at different values of ratio h/a (Poisson's ratio = 0.35).



teria. Those assumptions are as follows:

1. Gravel road consists of only two layers, namely, gravel layer and subgrade;
2. Design criterion is allowable subgrade stress; and
3. Gravel layer E-modulus depends on E-modulus of subgrade.

The first assumption has been made because of the complexity of the layer combinations in the section and their assumed bearing-capacity interaction, especially when layer thicknesses are 3-10 cm.

Allowable Stress as Design Criterion

The design criterion concerning the subgrade could have been the strain or the deformation. The strain criterion is replaced by the stress criterion because they express the same thing:

$$\epsilon_z = (1/E_u)\,[\sigma_z - \nu(\sigma_r + \sigma_\theta)] \quad (10)$$

Along the loading axis, $\sigma_r = \sigma_\theta$:

$$\sigma_z = k \cdot E_u \cdot \epsilon_z \quad (11)$$

$$k = 1 + [(2\nu \cdot \sigma_r)/(E_u \cdot \epsilon_z)] \quad (12)$$

The value k could be evaluated by varying E_1/E_u from 1 to 1000 and for various ratios of h/a (thickness of gravel to the radius of the loaded area). Calculation by the theory of elasticity gives Figure 12 (5); i.e., $k \approx 1$.

If we assume that Poisson's ratio is the same in all layers, the σ_z-criterion corresponds to the ϵ_z-criterion especially in our case, i.e., when the E-modulus of the gravel depends on the E-modulus of the subgrade (E_1/E_u = 2-4) and the thickness of the gravel layer is 30-70 cm.

The subgrade deformation criterion has been omitted because of its inconsistency with most of the design methods with which BYA constructions are comparable [cf. Broms (5)].

Dependence of Gravel E-Modulus on Modulus of Subgrade

The relation between the moduli of the upper layer and the subgrade has been studied by many researchers by measuring subgrade stress. Heukelom and Klomp (3) have studied a number of structures by the wave-propagation method and found that the ratio E_1/E_u varied between 1 and 3. They have even explained this relation theoretically.

This ratio tends to increase with weak subgrades and thick upper layers. In this case, considering the complicated layer combination, which could be encountered, and in general the uncertainty associated with low-volume roads, the assumption regarding E_1/E_u could be considered sufficient, because it gives better correlation with the field tests and because it is on the safe side, especially when the subgrade in question has a low bearing capacity. The ratio is not constant all year round, because the subgrade material is more sensitive to the climate variations and the groundwater level. However, the relation suggested by Heukelom and Klomp (3) has been adapted in this study because it showed the best correlation with actual measurements.

PRACTICAL ASSOCIATED PROBLEMS AND DESIGN GUIDE

There are a number of associated problems concerning this deflection-measuring process:

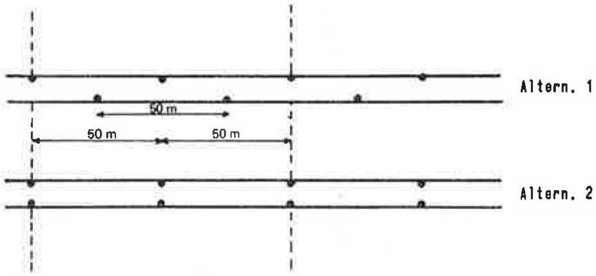
1. Distance between measurements,
2. Load magnitude,
3. Seasonal variation of measuring values,
4. Variation along transverse section, and
5. Correction of deformation value (decrease in peak load with deformation magnitude).

Distance Between Measuring Points

This distance should be chosen so that an adequate number of measurements can be obtained along the length of the road in order to have an adequate sectioning of the road with respect to bearing capacity. This is, in its turn, related to the ability of the paving machine to increase or decrease the layer thickness without a substantial delay in executing the job. The number of measurements is also governed by the minimum accepted kilometerage that the FWD should cover during a certain period. It has been agreed that 50 m along the wheel track is a reasonable distance between measurements, and a proposed distribution of measuring points along two opposite right-wheel tracks is shown in Figure 13.

If the minimum length of constant pavement thickness is 100 m, the minimum number of measurements according to Figure 13 is 5. If measurements are distributed symmetrically, the number of measure-

Figure 13. Alternatives in spacing of measuring points.



ments would be 6. However, due to the location of points opposite each other, alternative 2 gives no advantage. It was still chosen, however, because it was found more convenient.

Load Magnitude

The allowable stresses according to the E-modulus of the subgrade have been determined in this study by analysis of standard sections that have been in service for a rather long time. Those allowable stresses should not be exceeded; on the other hand, assumed values of those E-moduli were suggested within a certain range of stresses. Since most materials, especially subgrade materials, are nonlinear, it follows that the stress applied by the FWD should not exceed a certain level, because if higher stresses are applied, an E-modulus lower than the real one would be obtained, which would result in a lower allowable stress. This would mean that the pavement was overdesigned.

Evidence of nonlinearity has been obtained from field tests with an FWD [Figure 14 (7)] as well as from laboratory tests, for example, triaxial tests [Figure 15 (8)], which indicates that a difference of about 20 percent could be obtained when the stress is reduced from 0.7 to 0.35 MPa.

If the thickness required is more than about 40 cm according to the design chart (Figure 10), the load should be reduced by half, and the deformations D_0 and D_x should be multiplied by 2 before use of the same chart for the thickness design at a peak load of 25 kN. The difference between the thickness determined at 50 kN and that at 25 kN could be 5 cm or more when the gravel thickness needed is about 50 cm.

Seasonal Variation of Measuring Values

The seasonal variation in deflection values is influenced by the following factors:

1. Subgrade frost susceptibility,
2. E-modulus variation with water content,
3. Geometrical location of the section,
4. Level of the water table, and
5. Drainage adequacy along the road.

Figure 16 illustrates the seasonal variation of the mean value of V over the whole length of a gravel road. It is obvious that some sections would show a greater variation (and some less). However, Figure 16 indicates that a single measurement during the year cannot be used for thickness design.

The variation illustrated is not only a result of the frost action but is also a result of the change in level of the water table.

The variation of the bearing capacity with change of the water table has been studied at the National Swedish Road and Traffic Research Institute (9).

Figure 14. Dynamic plate-loading tests on subgrades.

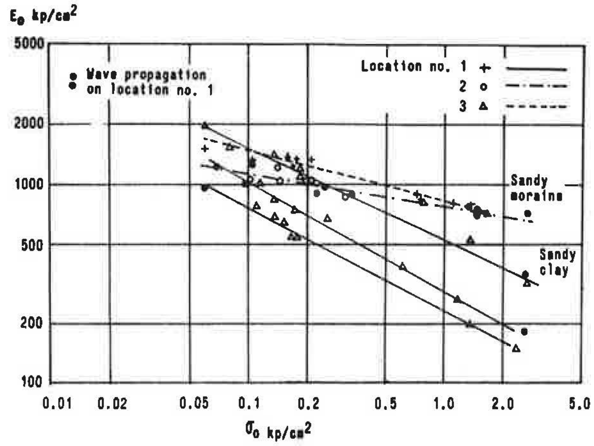


Figure 15. Results of triaxial tests.

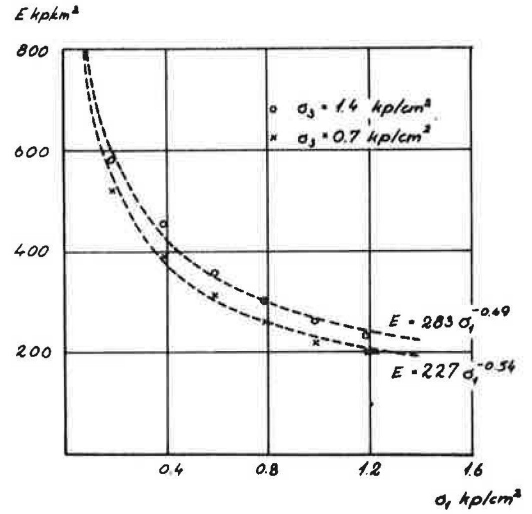


Figure 16. Seasonal variation of V.

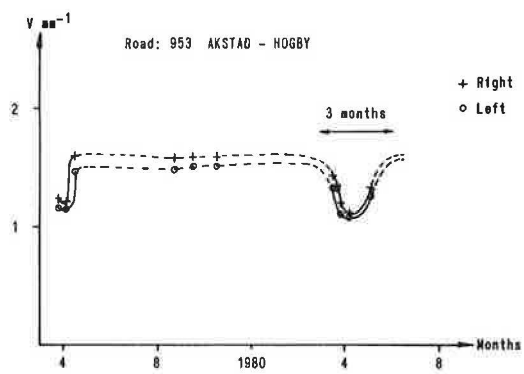


Figure 17 shows the resulting effect on E_u by raising the water level from far below the gravel surface to 70 and 30 cm below the surface. Measurement with the FWD during various seasons would give the whole picture of the year-round variation of the bearing capacity at every section, which would make rational design more attainable.

The seasonal bearing-capacity variation at any section would look like the variation of the mean value of the whole road with season as shown in Figure 16. On the other hand, it should be kept in mind that the possibility of performing several measurements year round is limited by cost.

Figure 17. FWD modulus values at different water-table levels.

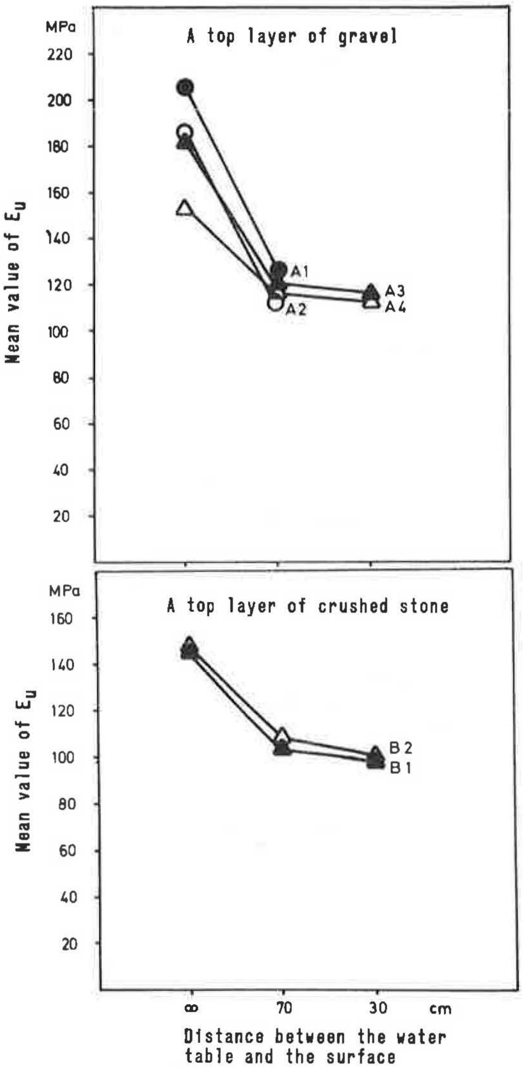
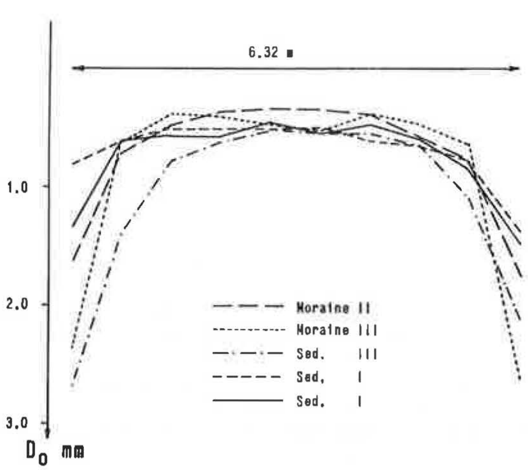


Figure 18. Variation of FWD deflection D_0 across gravel road (mean of several roads).



The bearing capacities during both the thaw period and the summer and fall periods should be taken into account for the thickness design. We have seen that $(1/D_x) - (1/D_0) = V$ is related to the E-modulus of the subgrade and by applying the equation proposed by Broms (4), which is derived from Miner's hypothesis,

$$(CBR)_m/(CBR)_3 = \left\{(t_2/12)\,[(CBR)_2/(CBR)_3]^{-b/a} + (t_3/12)\right\}^{-a/b} \quad (13)$$

where

- b/a = 1.25-3.31 (3.31 for completely unbound materials),
- CBR_m = design California bearing ratio,
- CBR_3, CBR_2 = CBR for summer-fall and thaw periods, and
- t_3, t_2 = duration of summer-fall and thaw periods.

By writing

$$CBR_2/CBR_3 = [(1/D_x) - (1/D_0)]_2/[(1/D_x) - (1/D_0)]_3 = V_2/V_3 \quad (14)$$

one arrives at

$$V_m/V_3 = \left\{(t_2/12)\,[(V_2 - 3.31)/V_3] + (t_3/12)\right\}^{-1/3.31} = F_{th} \quad (15)$$

The last equation could be used for the design, weighing the various bearing capacities. Two or more measurements in every period could be used to obtain the values of V_2 and V_3, one at least in the thaw period to obtain the mean bearing capacity in that period.

$$V_2 = (V_2' + V_2'')/2 \quad (16)$$

The time elapsed between those two measurements should be half the usual duration of the thaw period, i.e., $1/2t_2$, and it is preferable to perform more than one measurement in the summer-fall period since the bearing capacity during this period is the determining factor in the equation.

Variation Along Transverse Section

This variation has been studied at the Royal Institute of Technology in Sweden (10). Figure 18 illustrates that the bearing capacity increases towards the centerline of the road, and measurement in the right wheelpath could be considered representative.

Correction of Deformation Value

The loading magnitude remains as intended as long as deformation is rather small. A greater deformation will reduce the stress to be applied as shown in Figure 19 due to the influence of deflection on the dynamic loading process.

According to O. Tholén, in order to make comparison possible between all deformation levels, a correction factor should be applied in the following way:

$$N = 50.25 - 1.33D_{01} \quad (17)$$

where N is the real applied load and D_{01} is the deformation obtained. The correction factor is

$$K = 50/(50.25 - 1.33D_{01}) \quad (18)$$

$$D_0 = KD_{01} = D_{01}/(1 - 0.026D_{01}) \quad (19)$$

$$D_x = D_{x1}/(1 - 0.026D_{01}) \quad (20)$$

Figure 19. FWD peak load on different subgrades.

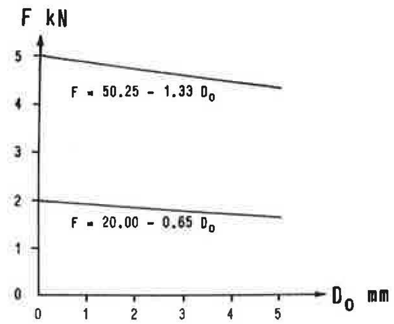
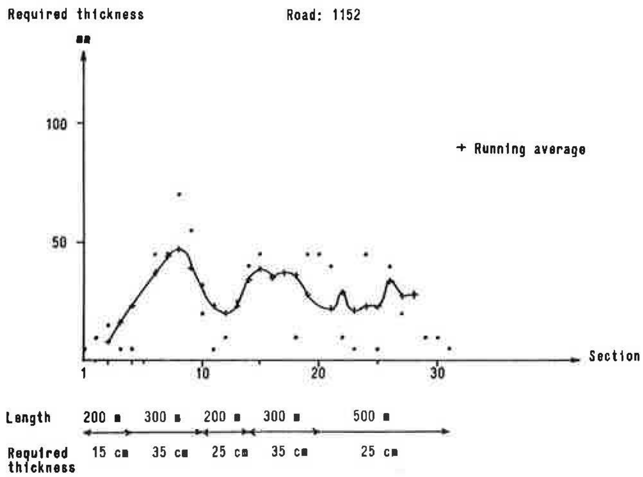


Figure 20. Example showing required overlay thickness along road.



The design process is summarized in the following steps:

1. Perform at least three measurements on the road on section intervals of 50 m, two during the thaw period (with half the thaw-period duration between them) and one in the summer-fall period;
2. Compute the corrected deformation, which corresponds to 50 kN according to the equations above;
3. Compute the factor F_{th} according to the duration of the thaw period t_2 and summer-fall duration t_3 by Equation 15 for every section;
4. Compute the following design parameters:

$$V_m = V_3 F_{th} \quad (21)$$

$$D_{0m} = D_{03}/F_{th} \quad (22)$$

5. Find the needed gravel thickness from Figure 10 for every section; and
6. Apply the running-average principle and divide the road into subsections, each with unified required thickness as follows:

$$H_{i,\,run} = (H_{i-2} + H_{i-1} + H_i + H_{i+1} + H_{i+2})/5 \quad (23)$$

where H_i is the needed thickness of subsection i. A curve like the one shown in Figure 20 would be obtained. If the road is to be divided into sections with a minimum length of 100 m and a thickness interval of 5 cm, the division is shown in Figure 20.

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