SHELL PROCEDURE FOR ASSIGNING MODULI TO UNBOUND GRANULAR MATERIALS

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The Shell procedure for assigning moduli to unbound granular materials is discussed. The results of the studies of the full-scale test section are analyzed, and some special features of the California bearing ratio equation are reviewed. It is shown that a distinct difference in performance exists among granular materials of different qualities. Moduli determined by using the Shell procedure seem to be reasonable for subbase and low-quality base materials. However, for pavements with thick, high-quality, well-graded, and well-compacted crushed-stone base materials, moduli higher than those determined by using the Shell procedure should be considered.

•IN 1965, Shell Oil Company (1) first published its procedure for assigning modulus values to unbound granular materials. Since then, because of the lack of a better and simpler procedure, it has been adopted widely by engineers for pavement design and analysis. The merit of the procedure, however, has been difficult to evaluate because of lack of adequate experimental data. Recently, the U.S. Army Engineer Waterways Experiment Station (WES) completed a series of full-scale accelerated traffic tests that provides an adequate amount of experimental data to evaluate the procedure (2). An analysis of results of these tests and a review of some special features of the California bearing ratio (CBR) equation revealed that, for flexible pavements with thick, high-quality, and well-graded crushed-stone base layers, the Shell procedure is inadequate; i.e., the determined moduli tend to be too low, and the pavements are overdesigned. This development is explained in this paper.

SHELL PROCEDURE

Figure 1 (4) shows the relationship developed by Dorman and Metcalf (1), between the modular ratio $K_2(E_2/E_3)$ and thickness of granular base. The ratio varies according to the thickness of the granular layer to allow for the surcharge effect. According to Dorman and Metcalf (1), the relationship (Figure 1) was arbitrarily chosen to give designs that correlate reasonably well with empirically developed CBR curves. They also stated that the development of this relationship was based, to some extent, on work by Heukelom and Klomp (3) in which a portable vibrator was used to measure dynamic E modulus values of road materials. Table 1 (3) gives the types of base course materials and dynamic moduli determined with this method. Slag, rolled brick, rubble, hand-pitched material, river gravel, gravel sand, and mechanically stabilized base were used.

In the Shell procedure, no distinction is made between base and subbase materials, and the average modulus of the entire granular layer is determined based on the thickness of the layer and the modulus of the supporting subgrade. The modulus is also independent of the magnitude of the load and the modulus and thickness of the overlying asphalt concrete (AC) layer.

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Figure 1. Modular ratio K_2 versus thickness of granular base.

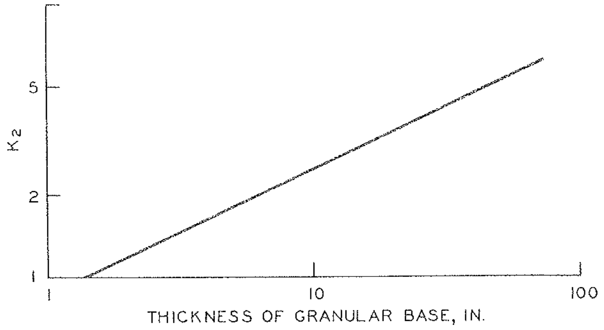


Table 1. Dynamic E moduli of unbound base course materials.

Location	$E_{subgrade}$	Type	E_{base}	Ratio of E_{base} to $E_{subgrade}$
Rotterdam, Holland	1,350	Slag	3,200	2.4
Utrecht, Holland	1,530	Rolled brick	5,300	3.5
England	1,860	Rubble	2,690	1.4
England	2,400	Hand-pitched	4,670	1.9
Lahr, Germany	2,400	Hand-pitched	3,150	1.3
Fontenay, France	2,800	Gravel	7,800	2.8
Ospel, Holland	3,000	River gravel	7,400	2.5
England	3,000	Rubble	4,700 to 6,700	1.6 to 2.2
Fussen, Germany	5,900	Gravel sand, compacted in two layers	20,000	3.4
	7,500	Mechanically stabilized base	14,500	1.9

Table 2. Multiple-wheel test data.

Pavement	Aircraft Type[a]	Assembly Load (kips)	Tire Contact Area (in.^{2})	Thickness (in.) Surface	Base	Subbase	Subgrade CBR	Coverages at Failure
1	Boeing 747	240	290	3	6	24	3.8	40
2	Boeing 747	240	290	3	6	24	4	40
3	Boeing 747	240	290	3	6	32	4	280
4	C-5A	360	285	3	6	6	3.7	8
5	C-5A	360	285	3	6	24	3.8	1,500
6	C-5A	360	285	3	6	24	4	1,500
7	C-5A	360	285	3	12[b]	0	4	98
8	C-5A	360	285	15	0	0	4	425
9	C-5A	360	285	3	6	15	4	104
10	C-5A	360	285	9	0	15	4	734
11	C-5A	360	285	9	15[b]	0	4	2,198
12	C-5A	360	285	3	21	0	4	5,000
13	Boeing 747	200	285	3	21	0	4	890

Note: 1 in. = 2.54 cm. 1 kip = 4448 N. 1 in.^{2} = 6.45 cm^2.

[a] Tests were performed by using a twin-tandem assembly, which represented one twin-tandem component of the Boeing 747 assembly, and a 12-wheel assembly, which represented one main gear of a C-5A assembly.

[b] Asphalt stabilized.

ANALYSIS OF FULL-SCALE ACCELERATED TRAFFIC TESTS

A series of traffic tests using multiple-wheel heavy gear loads has been recently conducted at WES. Pertinent data from these tests are given in Table 2. Unless otherwise stated, the granular base course materials in Table 2 consisted of clean, sound, durable particles of crushed stone and screenings. The aggregates were well-graded and were compacted to a density in excess of 100 percent of test CE-55 maximum density (4). The materials tested at WES were much stronger than those observed by Heukelom and Klomp (3). The subbase materials consisted of coarse-grained sand with gravels and were compacted to 100 percent of test CE-55 maximum density. (The CE-55 test method is similar to ASTM D 1557, method D.) Pavements 1, 2, 3, 4, 5, 6, and 9 in Table 2 were conventional flexible pavements; pavements 7, 8, and 11 were full-depth AC pavements; pavement 10 had a 9-in. (22.9-cm) AC surface and a 15-in. (38.1-cm) granular subbase; and pavements 12 and 13 had a 21-in. (53.3-cm) granular base.

The observed pavement performance was expressed in terms of coverages to failure. The failure criteria for these tests were based on cracking and rutting of the pavements. Simulated C-5A and Boeing 747 assemblies were used to apply the traffic. Although the total load of the C-5A assembly [360 kips (1 601 360 N)] applied to pavement 12 was heavier than that of the Boeing 747 [200 kips (889 644 N)] applied to pavement 13, the gear configurations are such that the load is more concentrated for the Boeing 747 than for the C-5A and, thus, causes more damage to the pavement. The same reasoning can be applied in comparisons of pavements 1 (or 2) and 5 (or 6).

Since the test pavements given in Table 2 primarily failed in the subgrade soil and since it is believed that a correlation exists between subgrade strain and pavement performance, an analysis was made that involved computing the maximum vertical strains at the top of the subgrade of each test pavement. The computed values were then plotted against the observed performance of each pavement. These relationships are shown in Figure 2. The curve represents the best fit line and does not consider the data points for pavements 12 and 13. The BISTRO computer program was used in the computations. The modulus of the AC layer was determined from the measured average pavement temperature during the traffic period, the modulus of the granular layer was determined from the relationship shown in Figure 1, and the modulus of the subgrade was calculated by using the relation E = 1,500 CBR (5). The values of Poisson's ratio for the AC, the granular layer, and the subgrade soils were 0.4, 0.45, and 0.4 respectively.

Figure 2 shows that, although the correlations are not at all bad between the vertical subgrade strains computed by using the Shell procedure for determining the moduli for granular materials and the observed pavement performance, a considerable discrepancy exists for pavements 12 and 13. These were the only two pavements with thick, high-quality, well-graded, and well-compacted crushed-stone bases. The performance for pavements 12 and 13 would be 100 and 200 coverages respectively, instead of the 5,000 and 890 actually observed, if the moduli of their high-quality granular bases were determined by using the Shell procedure. If moduli higher than those determined by using the Shell procedure were used in the computation, the computed subgrade strains would be reduced. The points for pavements 12 and 13 would thus move to the best fit line on Figure 2. It therefore appears that, based on the full-scale accelerated traffic test results, moduli determined by using the Shell procedure are too low for high-quality, well-graded, and well-compacted crushed-stone base materials.

ANALYSIS OF PAVEMENTS DESIGNED BY CBR EQUATION

For this study, a number of pavements were designed at different coverage levels based on the CBR equation (6). The magnitude of the wheel load, the thicknesses of component layers, and the subgrade CBR of each pavement are given in Table 3. The required thicknesses of AC and base course of the pavements under different wheel loads were determined by standard flexible pavement design procedure of the Corps of Engineers.

The vertical subgrade strains at the top of the subgrade were then computed for each pavement. In these computations, a constant modulus of 100,000 psi (689 500 kPa) was

Figure 2. Vertical strain at subgrade surface versus performance of pavement system under multiple-wheel loads.

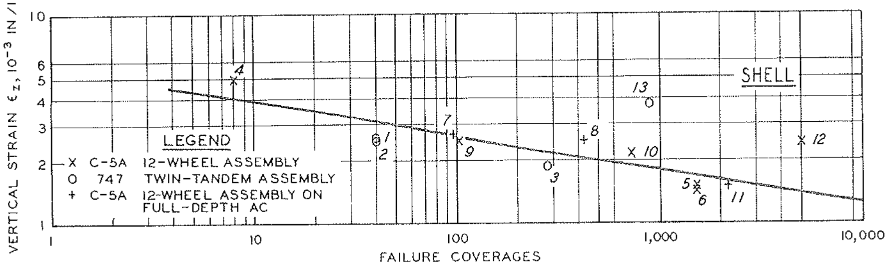
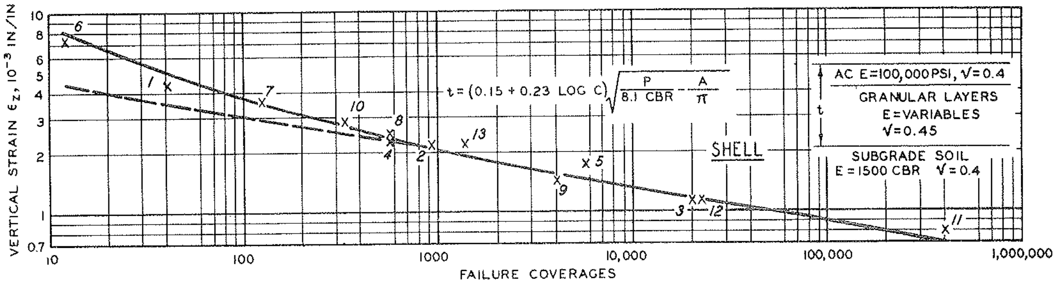


Table 3. Pavements designed by CBR equation.

Pavement	Single-Wheel Load (kips)	Tire Inflation Pressure (psi)	Thickness (in.) Surface	Base	Subbase	Subgrade CBR	Coverages at Failure
1	30	105	3	6	6	4	40
2	30	105	3	6	15	4	913
3	30	105	3	6	24	4	20,000
4	30	105	3	6	6	8	549
5	30	105	3	6	6	12	5,750
6	50	175	3	6	6	4	12
7	50	175	3	6	15	4	125
8	60	207	3	6	24	4	575
9	60	207	3	6	32	4	3,990
10	50	175	3	6	6	12	331
11	60	207	3	6	24	12	408,000
12	60	207	3	6	24	8	22,400
13	50	175	3	6	6	16	1,380

Note: 1 in. = 2.54 cm. 1 kip = 4448 N. 1 psi = 6.895 kPa.

Figure 3. Vertical strain at subgrade surface versus performance of pavements designed by using the CBR equation.



assigned to the AC surface layer. The modulus values of the granular layers were determined from the Shell procedure (Figure 1) and were based on the thickness of the base and subbase layers and the strength of the subgrade soil. For the subgrade soil, the relation E = 1,500 CBR was used to convert the CBR values into modulus of elasticity E values for use in the computer program.

The relationships between failure coverages and computed vertical strain values are shown in Figure 3. The solid curve is the best fit line going through the points. The Shell procedure for assigning values to granular materials indeed correlates reasonably well with the CBR performance equation (1). However, some special features of the CBR equation in relation to granular layers should be pointed out. Conventional flexible pavements designed by using the CBR equation generally consist of a thin layer of AC surface course [usually 3 in. (7.6 cm)], a layer of high-quality, well-graded, and well-compacted crushed-stone base with nominal thickness [generally 6 in. (15.2 cm)], and a thick layer of sand and gravel subbase. The thickness of the subbase depends on the load, the subgrade strength, and the design coverage level. All of the 13 pavements designed by using the CBR equation had a 6-in. (15.2-cm) base layer; however, the thicknesses of the subbase layers varied from 6 to 32 in (7.6 to 81.3 cm) (Table 3). In most of these pavements, the thickness of the subbase was much greater than that of the base; this relationship is particularly true of pavements designed for high coverage levels. Therefore, the response of pavements designed by the CBR equation to load is controlled, in most cases, by the thick subbase layer rather than by the relatively thin base layer. This is particularly true when the vertical subgrade strain is the primary concern. It follows then that, since the Shell procedure makes no distinction between base and subbase materials but correlates reasonably well with the CBR equation, the moduli determined by using the Shell procedure apparently represent those of sand and gravel subbase and not those of high-quality, well-graded, and well-compacted crushed-stone base. For pavements with thick, high-quality base layers, the moduli determined by using the Shell procedure are apparently too low. This can be seen in the results from pavements 12 and 13 (Figure 2).

CONCLUSIONS

Full-scale field studies indicate that a distinct difference in performance exists between granular materials of different qualities. Moduli determined by using the Shell procedure seem to be reasonable for subbase and low-quality base materials. However, for pavements with thick, high-quality, well-graded, and well-compacted crushed-stone base materials, moduli higher than those determined by using the Shell procedure should be considered.

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