The Evaluation of Plate Bearing Test Data of Flexible Airfield Pavements

Evaluation des essais de charge sur plaque pour les pistes d'atterissage flexibles

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SUMMARY

Problems encountered in strength assessment of airfield pavements in Central Africa necessitate performing plate bearing tests at depth. The paper describes the extension of established theories into a method of co-relation of surface and subsurface data, based on a "pressure circle" assumption of soil stress distribution, and introduces the concept of the equivalent plate load (E.P.L.), supplementing the load classification number system. A graphical presentation of co-relating aircraft stress requirements with pavement strengths at varying depths is introduced.

SOMMAIRE

Pour résoudre les problèmes rencontrés lors de l'évaluation de la résistance des pistes d'atterissage d'Afrique Centrale, il est nécessaire d'effectuer en profondeur des essais de charge sur plaque. L'article explique comment, à partir des théories déjà connues, a été développée une technique reliée aux caractéristiques des sols de surface et des couches sous-jacentes, et basée sur l'hypothèse que les efforts à l'intérieur du sol se répartissent suivant un "cercle de pression." Cette étude nous amène à envisager le concept de charge equivalente de plaque (E.P.L.) qui vient compléter la méthode de Numero de Classification de Charge. Une représentation graphique donne les relations entre les contraintes à l'atterrissage des aéronefs et la résistance des revêtements à différentes profondeurs.

Aerodrome Test Conditions

MOST CENTRAL AFRICAN AERODROMES, developed in stages by pavement extensions and overlays from flying fields for small aeroplanes to standards suitable for contemporary aircraft, show considerable variations in pavement characteristics. Subsequent gravel and premix overlays have often resulted in semi-rigid layers formed with insufficient cover over old substrata. These facts preclude plate bearing test evaluation by methods applicable to more homogeneous construction (Burmister, 1945; McLeod, 1947; McLeod, 1953; Yoder, 1959) and subsurface tests become imperative. Surface tests are not carried out at all, because diurnal temperature variations exceeding 80 F (air temperature) affect Young's modulus of premix surfacings. By night, pavement flexibility may occur, but an afternoon test may show considerable plate penetration with heaving around the plate.

Aerodromes have one main runway, and since distances between aerodromes make air traffic diversions impracticable, pavement tests must be carried out during time gaps in aircraft movements. Subtropical rainfall restricts the period of high subsoil moisture content, and therefore the conditions necessary for testing, to four months per year.

Under these circumstances, it becomes essential to discover weak pavement sections early during the tests to avoid unnecessary tests on sections of more than adequate strength; to convert subsurface to surface strengths; to reduce individual tests to the smallest number of load repetitions necessary to separate true fatigue from other components of plate movements (e.g., compaction, consolidation) while ensuring sufficient load repetitions for a reliable fatigue strength assessment; and to evaluate a test immediately after its completion so that a new test point in a weak section can be selected even before the equipment has been fully dismantled. The methods evolved to satisfy these requirements are described in this paper. Also described are a test data presentation which permits strength assessments according to the financial resources available for maintenance and reconstruction, and cover design diagrams for the increase of existing pavement or subgrade strengths.

Origin of Evaluation Methods

The methods described have been developed from previously published theories, supplemented by experience gained mainly by British authorities. They are based on the Boussinesq equation modified by the British Air Ministry (Boussinesq, 1885; British Air Ministry, 1952, 1957, 1959):

$$\sigma_h = \sigma \times \sin^2\alpha \tag{1}$$

and the relationship of test plates of varying diameters and the loads thereon which cause identical deformations,

$$W/W_h = (A/A_h)^{0.44}$$

or, in terms of plate diameters,

$$W/W_h = (d/d_h)^{0.88}. \tag{2}$$

THE EQUIVALENT PLATE LOAD

The Equivalent Plate Load (E.P.L.) concept derives from the Equivalent Isolated Single Wheel Load (E.S.W.L.) and the Load Classification Number (L.C.N.) theories. The E.P.L. affords a more convenient and direct comparison of pavement failure loads and aircraft requirements than the L.C.N.

While the E.S.W.L. represents the load of an imaginary single wheel on a pavement surface which, at any specified depth, produces vertical stresses identical to those caused at the same depth by the combined wheels of one leg of an aircraft landing gear, the E.P.L. is a conversion, in accordance with Eq 2, of the E.S.W.L. to its equivalent on a plate of specified diameter. This diameter (in inches) is quoted in brackets following the letters E.P.L., e.g. the equivalent plate load on a 21-in. diam plate for a V.C.10 at 299,000 lb all-up weight and 115 lb/sq.in. tyre pressure at a depth of 40 in. is shown as E.P.L. (21) = 56,400 lb.

E.P.L. values are obtained graphically from Fig. 1. (Point A through Point B to Point C shows E.P.L. (21) for the V.C.10.) Table I gives E.P.L. values on a 21-in. diam plate for aircraft in use in Central Africa. Prior to testing, the E.P.L. values for aircraft using the pavement to be tested are entered in Fig. 2. At this stage, the size of the plate to be used is not known, and a copy of Fig. 2 is prepared for each size of plate.

TABLE I. E.P.L. (21) DATA OF AIRCRAFT IN USE IN CENTRAL AFRICA

Aircraft	All-up weight (lb)	Tyre pressure (lb/sq.in.)	Equivalent plate load (lb) on 21 in. ϕ-plate at depth of 0 in.	10 in.	20 in.	30 in.	40 in.
B.A.C. 1-11 (200)	73,500	117	25,200	28,900	32,800	35,100	36,900
B.A.C. 1-11 (300)	82,000	117	26,900	31,300	35,200	37,600	39,500
B.A.C. 1-11 (400)	78,500	117	26,000	30,200	34,100	36,400	38,300
Boeing 707 (320)	280,000	142	38,900	41,100	48,200	54,300	59,000
Britannia 310 L.R.	175,000	139	30,000	36,700	43,500	47,900	51,100
Canadair	80,200	100	23,900	25,900	29,500	31,900	33,700
DC 4	73,000	75	21,300	22,200	25,300	27,300	28,800
DC 6 B	107,000	106	30,700	32,000	36,500	39,300	41,500
DC 8	278,500	128	38,000	41,300	50,100	55,900	60,200
Viscount 701	60,000	106	21,300	25,100	28,200	30,100	31,300
Viscount 802	62,000	111	22,100	25,900	29,200	31,300	32,600
VC 10	299,000	115	36,800	38,300	46,500	52,000	56,400

THE CORRELATION OF SUBSURFACE AND SURFACE TEST RESULTS

Because the correlation of subsurface and surface test results has been a matter of guess work in the past, a conversion method was evolved.

The Pressure Circle

The vertical stresses in a plane at depth h below a test plate decrease as the horizontal distance of the stressed point from the vertical axis through the plate increases and the load is spread over an area larger than that of the surface plate. Ignoring—provisionally—the stress decrease, but assuming that the stress below the centre of the plate at depth h, calculated according to Eq 1, is evenly distributed over a circular area, an imaginary pressure circle is obtained, of which the radius-to-load relation

$$r_p^2 = W/(\pi \times \sigma_h). \tag{3}$$

Because $\sigma = W/(\pi \times r^2)$ and $\sin \alpha = r/\sqrt{(r^2 + h^2)}$, Eq 1 becomes

$$\sigma_h = W/\pi \times (r^2 + h^2) \tag{4}$$

and Eq 3 becomes

$$r^{\,2} = r^2 + h^2$$

or, in terms of pressure circle diameter

$$d_p^2 = 4r^2 + 4h^2. \tag{5}$$

Were the vertical stresses in the horizontal plate at depth h equal at all points, a subsurface plate of diameter d_p would represent a surface plate of diameter d, but because equal stress distribution exists only near the vertical axis through the surface plate, the diameter of the subsurface plate should not exceed that of the plate chiefly used for surface tests. The subsurface plate will be smaller than the pressure circle, and the applied load W_h will be less than the surface load W.

Pressure Circle and Subsurface Plate

In accordance with Eq 2, the relation between pressure circle load (= surface load) W and subsurface plate load W_h is $W/W_h = (d_o/d_h)^{0.88} = C$ where C is a load factor, and the subsurface/surface load relationship is

$$W = C \times W_h \tag{6}$$

and

$$W_h = W/C \tag{7}$$

The Load Factor Diagram

The load factor diagram (Fig. 3) offers a convenient way of converting subsurface to surface loads. The surface plate diameter in the upper part of the diagram intersects at the specified (horizontal) depth line the (vertical) pressure circle diameter line which—in the lower part—intersects the (diagonal) subsurface plate diameter line at the (horizontal) load factor line. For example: a load of $W_h = 32{,}700$ lb on an 18-in.-diam subsurface plate at a 12¼-in. depth causes fatigue failure. Required is the E.P.L.(21), i.e. the load which, on a 21-in.-diam surface plate, will cause an identical failure. The pressure circle diameter is 32.2-in. (Point A). Point B indicates a load factor C = 1.67. The E.P.L.(21) is the critical surface load $W = 32{,}700 \times 1.67 = 54{,}600$ lb.

THE EVALUATION OF AN INDIVIDUAL TEST

Soil Movements under Plates

The plate bearing test is a fatigue test involving measuring of the vertical movements of a plate under repeated loadings and load releases. Loading a plate (within the limits of elasticity of the pavement) results in downward movements of plate and pavement strata, in limited horizontal movements of soil particles, and in minor upward movements of particles outside the loaded area. Releasing the load causes a partial recovery of the pavement indicated by an upward movement of the plate. The lack of recovery, i.e. the settlement after the load release, is primarily due to compaction, consolidation (where subsoil moisture content is high), and flexural fatigue.

Compaction and similar components form the major part of deflection and settlement during the first load repetitions, but their influence diminishes as further loadings are applied. On dense pavements with a high Young's modulus, compaction components are often nearly eliminated after three loadings, but twelve or more load repetitions may be required on premix or highly plastic pavements before the fatigue component becomes prominent. The first task of the test engineer is to separate compaction, consolidation, and similar "disturbing" components from the fatigue component.

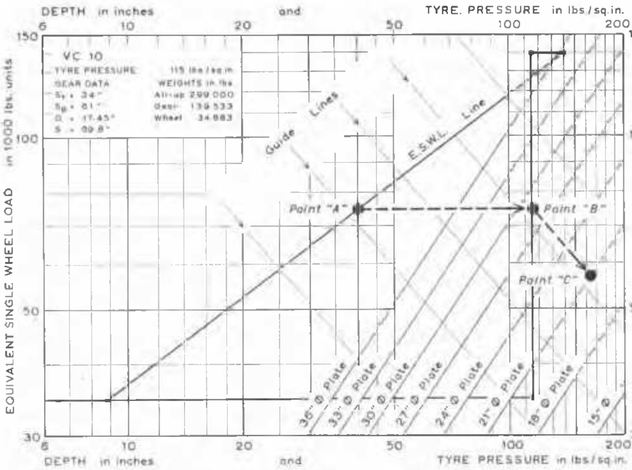

FIG. 1. Equivalent plate load diagram for aircraft.

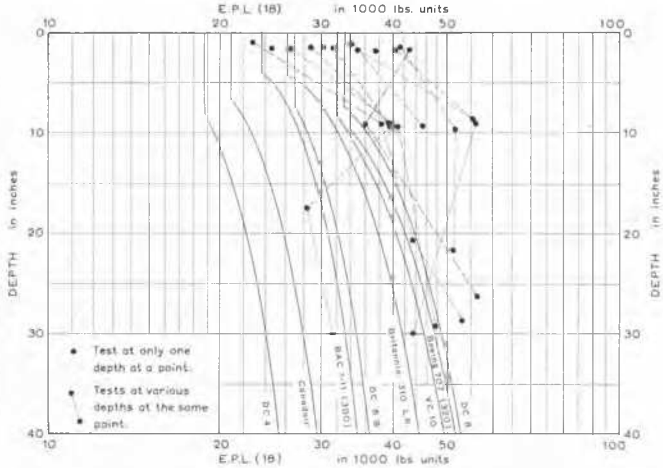

FIG. 2. Aircraft requirements and test results.

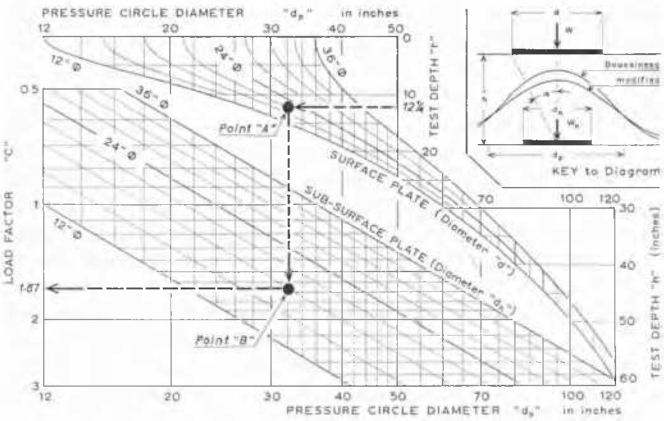

FIG. 3. Load factor diagram.

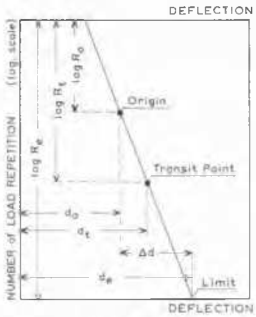

FIG. 4. Algebraic notations.

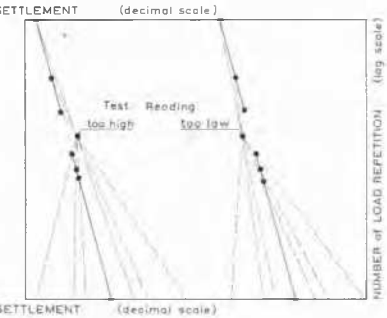

FIG. 5. Results of test errors.

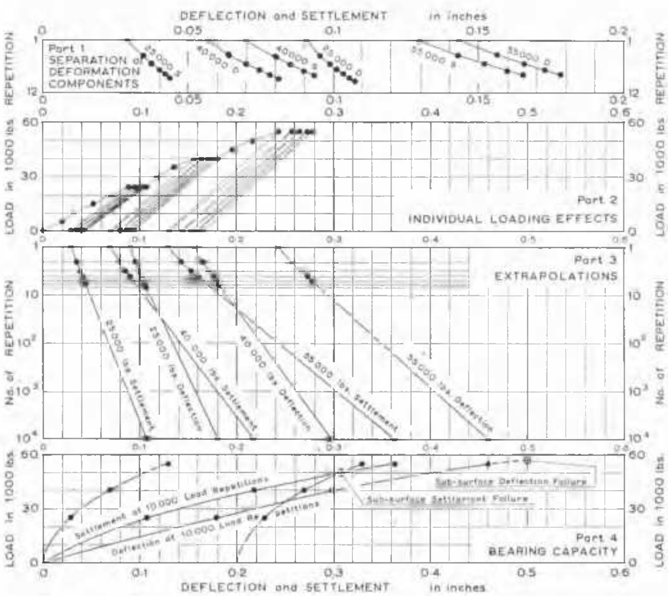

FIG. 6. Data recording and evaluation during test.

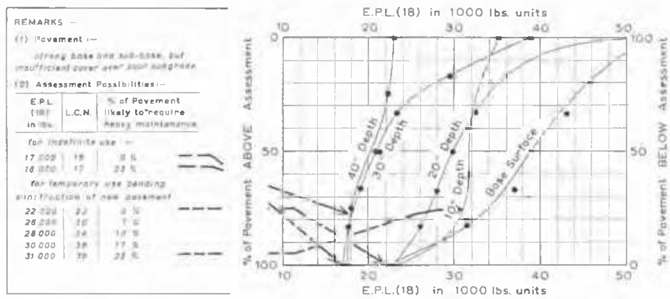

FIG. 7. Pavement fatigue strength assessment guide.

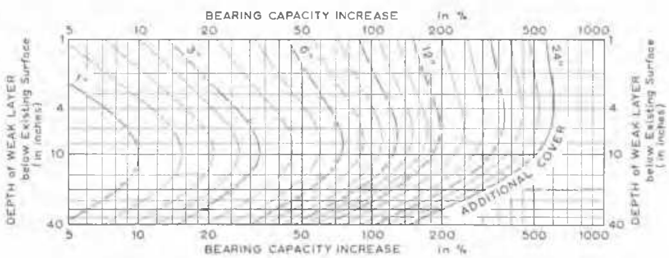

FIG. 8. Cover design diagram for 21-in. ϕ plate strength increase.

TABLE II. EXTRAPOLATION COEFFICIENTS FOR 10,000 LOAD REPETITIONS

Origin of extrapolation, load repetition number	Transit point of extrapolation, load repetition number										
	12	11	10	9	8	7	6	5	4	3	2
11	78.29										
10	37.89	72.48									
9	24.38	34.95	66.56								
8	17.59	22.39	31.96	60.54							
7	13.48	16.07	20.37	28.91	54.40						
6	10.70	12.24	14.53	18.30	25.79	48.13					
5	8.68	9.64	10.97	12.93	16.17	22.59	41.69				
4	7.12	7.73	8.54	9.65	11.29	13.98	19.30	35.06			
3	5.85	6.24	6.74	7.38	8.27	9.57	11.70	15.88	28.12		
2	4.75	5.00	5.29	5.66	6.14	6.80	7.75	9.30	12.29	21.01	
1	3.71	3.84	4.00	4.19	4.43	4.73	5.14	5.72	6.64	8.39	13.29

Algebraic Extrapolation

In order to facilitate the separation of the deformation components and to evaluate test results before the test equipment has been fully dismantled (to permit a selective rather than an at random choice of further test points), the conventional graphic extrapolation has been supplemented by an arithmetic method which is used concurrently with the test.

Basis of calculations (Fig. 4, Table II). In accordance with the fatigue effect extrapolation principle,

$$d_e = d_0 + \Delta d_e$$
$$= d_0 + (d_t - d_0)$$
$$\times (\log R_e - \log R_0)/(\log R_t - \log R_0) \quad (8)$$

where d_e = deflection (or settlement) at extrapolation limit, d_0 = deflection (or settlement) at extrapolation origin, d_t = deflection (or settlement) at extrapolation transit point, R_e = number of load repetition at extrapolation limit, R_0 = number of load repetition at extrapolation origin, R_t = number of load repetition at extrapolation transit point. Table II shows the coefficient $(\log R_e - \log R_0)/(\log R_t - \log R_0)$ for an extrapolation limit of 10,000 repetitions.

EXTRAPOLATION from ORIGIN R_o	through TRANSIT POINT R_t	DEFLECTION in 0·001" units 7	6	5	4	3	2	SETTLEMENT in 0·001" units 7	6	5	4	3	2
	Reading d_t	106·5	105·0	103·2	100·8	97·7	95·4		43·8	42·2	40·3	37·2	34·4
6	Reading d_o	105·0											
	Difference d_t-d_o	1·5											
	Increase Δd	72											
	Total d_e	177											
5	Reading d_o	103·2	103·2						42·2				
	Difference d_t-d_o	3·3	1·8						1·6				
	Increase Δd	74	75						67				
	Total d_e	177	178						109				
4	Reading d_o	100·8	100·8	100·8					40·3	40·3			
	Difference d_t-d_o	5·7	4·2	2·4					3·5	1·9			
	Increase Δd	79	81	84					68	67			
	Total d_e	180	182	185					108	107			
3	Reading d_o	97·7	97·7	97·7	97·7				~~37·2~~	~~37·2~~	~~37·2~~		
	Difference d_t-d_o	8·8	7·3	5·5	3·1				~~6·6~~	~~5·0~~	~~3·1~~		
	Increase Δd	84	85	87	87				~~77~~	~~79~~	~~87~~		
	Total d_e	182	183	185	185				~~114~~	~~116~~	~~124~~		
2	Reading d_o	~~95·4~~	~~95·4~~	~~95·4~~	~~95·4~~	~~95·4~~			34·4	34·4	34·4	~~34·4~~	
	Difference d_t-d_o	~~11·1~~	~~9·6~~	~~7·8~~	~~5·4~~	~~2·3~~			9·4	7·8	5·9	~~2·8~~	
	Increase Δd	~~78~~	~~75~~	~~73~~	~~66~~	~~48~~			73	72	72	~~59~~	
	Total d_e	~~171~~	~~170~~	~~168~~	~~161~~	~~143~~			107	106	106	~~93~~	
1	Reading d_o	~~90·1~~	~~90·1~~	~~90·1~~	~~90·1~~	~~90·1~~	~~90·1~~		~~28·9~~	~~28·9~~	~~28·9~~	~~28·9~~	~~28·9~~
	Difference d_t-d_o	~~16·4~~	~~14·9~~	~~13·1~~	~~10·7~~	~~7·6~~	~~5·3~~		~~14·9~~	~~13·3~~	~~11·4~~	~~8·3~~	~~5·5~~
	Increase Δd	~~77~~	~~76~~	~~75~~	~~71~~	~~65~~	~~71~~		~~78~~	~~76~~	~~75~~	~~70~~	~~73~~
	Total d_e	~~167~~	~~166~~	~~165~~	~~161~~	~~153~~	~~161~~		~~107~~	~~105~~	~~105~~	~~99~~	~~102~~

Deflection — ANALYSIS:- *Compaction affects 1st and 2nd readings.*

RESULT:- $170 + \frac{1}{10}(7+7+8+10+12+15+12+13+15+15) = 170 + \frac{1}{10} \times 114 = 181$ = Total at Extrapolation Limit

Settlement — ANALYSIS:- *Compaction affects 1st reading, and 3rd reading is too low.*

RESULT:- $100 + \frac{1}{6}(9+8+7+7+6+6) = 100 + \frac{1}{6} \times 43 = 107$ = Total at Extrapolation Limit

Extrapolation Limit:- *10,000* Load Repetitions

Test Plate:- *18" Ø* Test Load:- *25,000* lbs. Test Depth:- *1⅜"*

CHART 1. EXTRAPOLATION DURING TEST

Test errors and compaction influence (Fig. 5, chart 1). If all deflections or settlements were solely due to pavement bending, if no test errors occurred, and if no compaction or similar influences were present, the calculated extrapolation values would be identical irrespective of the choice of origin and transit point of the extrapolation. A test error causes a scatter of extrapolation results which becomes larger the closer the extrapolation origin is to the transit point. Because each deflection (or settlement) reading—except the last one—is used as origin of an extrapolation through each subsequent reading (Chart 1), test errors can be easily identified. Compaction and similar deformation influences are identical to those of test errors. Throughout the test, errors are identified and eliminated, and further loadings are applied, until at least six extrapolated values differ by less than 5 per cent. The mean of the calculated extrapolation values remaining after elimination of test errors and compaction influences is accepted as final extrapolation. The error in the computed result rarely exceeds ± 2½ per cent while graphic extrapolation may—even under favourable conditions—be subject to errors of ± 10 per cent.

Graphic Extrapolation

The conventional graphic recording (Fig. 6, Part 2) and extrapolation (Fig. 6, Part 3) are also carried out while the test is in progress, the diagrams normally used having been combined in one single form to simplify the transfer of data from one to another. To facilitate the separation of the fatigue component from compaction and similar components, Part 1 (Fig. 6), has been introduced in which on an expanded scale only the last two or three decimals of deflection and settlement readings are entered (e.g. 0.2 in. is subtracted from all deflection readings of a series of loadings of which the first reading is 0.242 in.). Plotted on this diagram, the first readings, where compaction is a major component—will fall on a curve, but later readings—representing flexature—form a straight line. Test errors show as points off the straight line.

Determination of Failure Load

Once extrapolation values have been established and plotted in Parts 3 and 4 (Fig. 6) the failure load is determined graphically in accordance with conventional practice. This failure load represents the pavement capacity at the subsurface level at which the plate was placed. Converted to a surface failure load in accordance with the method described *supra* (p. 150), it becomes the equivalent plate load for the pavement at the tested depth at the test point and is entered in Fig. 2.

Tests at various depths at the same test "point" must be taken at horizontal intervals of about 10 ft, but they are treated in Fig. 2 as referring to the same point. A comparison in Fig. 2 of pavement E.P.L.'s. and aircraft E.P.L. requirements discloses pavement sections and layers of critical strength.

FINAL PAVEMENT STRENGTH ASSESSMENT

In order to permit an assessment of operating strength of a pavement in relation to the funds available for maintenance and reconstruction, tests are taken at approximately equal horizontal intervals. All results are plotted in Fig. 7, and points referring to the same test depth are connected. The operating strength can then be determined leaving an acceptable percentage (e.g. 5, 10, or 20 per cent) of the pavement subject to heavy maintenance or reconstruction expenditure.

PAVEMENT FATIGUE (PLATE BEARING TEST) DESIGN DIAGRAMS

If aircraft requirements at a certain depth exceed the existing pavement E.P.L., the pavement can be strengthened by additional cover. Once this cover has been provided, the vertical stress at the weak level will be

$$\sigma_{h+\Delta h} = \frac{W_c}{\pi \times r^2} \times \frac{r^2}{r^2 + (h + \Delta h)^2} = \frac{W_c}{\pi} \times \frac{1}{r^2 + (h + \Delta h)^2},$$

instead of, $\sigma_h = \dfrac{W}{\pi \times (r^2 + h^2)}$ before cover increase. Because the maximum permissible subsurface stress remains unchanged,

$$\sigma_h = \sigma_{h+\Delta h} = \frac{W}{\pi \times (r^2 + h^2)} = \frac{W_c}{\pi} \times \frac{1}{r^2 + (h + \Delta h)^2},$$

the load ratio becomes

$$\frac{W_c}{W} = \frac{r^2 + (h + \Delta h)^2}{r^2 + h^2} = 1 + \frac{2h\Delta h + \Delta h^2}{r^2 + h^2},$$

and the bearing capacity *increase* is

$$\Delta W = \frac{W_c}{W} - 1 = \frac{2h\Delta h + \Delta h^2}{r^2 + h^2}. \qquad (9)$$

Fig. 8 shows the pavement capacity increase/depth of weakest layer/additional cover relationship for E.P.L.(21). For example: a pavement E.P.L.(21) at a 30-in. depth is 45,500 lb, but a Boeing 707 (320) requires 54,300 lb. The necessary bearing capacity increase is

$$54{,}300/45{,}500 - 1 = 0.193 = 19.3 \text{ per cent.}$$

Fig. 8 indicates that 3 in. of additional cover is required.

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