CONCLUSION AND DISCUSSION

The status of the department's highway condition rating efforts is reviewed. Great progress has been made in the past 3 years in improving the consistency, accuracy, and quality of the highway condition data collected by New York and in providing it to a variety of clients in rapid and relevant fashion. Virtually all aspects of the highway condition assessment and data processing effort have been reviewed and streamlined. The big effort, in terms of methodology development, is over, and the procedure is now moving into an implementation and "shake-out" phase in which refinements to the methodology are becoming more detailed and fewer changes are occurring from year to year. Overall, the department is pleased with the methodology, and is placing greater reliance on the results of the survey and on the analyses that are conducted from it.

No highway condition assessment procedure should be static. Issues, highway conditions, and concerns change. The procedure being developed by the department is flexible and is capable of undergoing change to meet evolving needs, while at the same time retaining consistency in data so that trends may be computed. A fully integrated and static data base is probably beyond the need of the department, but it can be reasonably well approximated by the application of consistent measurement principles and a tightened rating and data provision process. This is the goal that the department is working toward, and it is the goal to which the department believes it has made considerable progress.

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Use of Pocket Computers for Rehabilitation of Rural Roads in Dominica

LOUIS BERGER and JACOB GREENSTEIN

ABSTRACT

A 50-km rural road that connects Roseau-Pont Casse and Hatton Garden in Dominica was evaluated by means of the Benkelman beam in February 1983. The rebound deflection basin obtained under a dual-wheel axle load was interpreted by means of a pocket computer with 8-K RAM. The subgrade modulus, subgrade California bearing ratio, base modulus, asphalt modulus, and the required asphalt concrete overlay were calculated for each point while performing the nondestructive testing (NDT) survey. Although measurement of deflection basins with the Benkelman beam is not common practice, satisfactory results were obtained. A team composed of the truck driver and his assistant, an experienced engineer and his assistant, and two traffic control men was able to measure 80 to 100 deflection basins, or about 10 km of road, in a typical working day. By using the pocket computer, all calculations, including the overlay thickness of each tested point, can be completed in about 1 min. Therefore, the road rehabilitation design can be completed while conducting the NDT. In Dominica both the NDT and the strengthening design of the 50-km road were done simultaneously and completed in 1 week. The detailed methodology and computer programs are presented in this paper. The program is based on the theory of linear elastic systems and written in BASIC language. It can be easily adjusted and implemented with other nondestructive pavement evaluation devices such as the road rater or the falling weight deflectometer.

In the evaluation process of pavement systems by means of nondestructive testing (NDT), the response of the pavement is observed and material properties can be back-calculated. Among the different responses of the pavement to load, the only practical measurements are elastic deflections. Two methods

for determining the elastic deflections are generally used. According to the first method (1-3), in each location only the center or the standard maximum deflection is determined. The magnitude of this deflection is interpreted to predict pavement performance.

In the second procedure, which is a rational one, the deflection basin (i.e., the center deflection) and at least one offset deflection are determined (4-7). The deflection basin is used to back-calculate the elastic modulus of the subgrade and pavement system. These strength parameters and the projected traffic loading are used to design pavement strengthening.

This rational procedure was implemented in Dominica by means of a pocket computer (Sharp PC-1500) to upgrade 50 km of low-volume road between Roseau-Pont Casse and Hatton Garden (see Figure 1). The computer program (Figure 2) is written in the BASIC language and can be implemented on any personal or pocket computer that has 8-K RAM. Because the program is based on the theory of the linear elastic system, it can be easily adjusted and used with other nondestructive pavement evaluation devices such as the road rater (pavement profiler) or the falling weight deflectometer.

BENKELMAN BEAM DEFLECTION PROCEDURE

The Benkelman beam is a widely used device to measure surface deflections in all types of pavement structures. The beam operates on the lever principle, as shown schematically in Figure 3. Every vertical movement of the tip of the beam generates a rotation of the beam through the pivot. A proportion of the tip movement is read with the dial gauge installed at the far end of the beam. The ratio of the rotating lengths of the beam is generally 1:4 (including the beam used in Dominica); thus the dial gauge (Figure 1d) at the end of the beam moves one-fourth of the vertical movement at the tip of the beam. Often the dial gauge is already calibrated to read the full tip movement (i.e., no multiplication by four is required).

The truck used in Dominica had a single dual-wheel rear axle weighing 7174 kg and a tire pressure of 4.9 kg/cm^2. This load was chosen instead of the commonly used 8200-kg axle load because Dominica truck loads seldom reach the 8200-kg level. The dual-wheel load (PP) (in kg) is specified in line 5050 in the program, and any value of PP can be used.

The so-called "rebound method" was used in the Benkelman beam measurements. The truck moved away from the testing point at creep speed, and the rebound deflections were measured. This method was used to measure not only the maximum deflection under the rear axle (D0), but also to measure two additional deflections--D40 and D80--at 40 and 80 cm away from the maximum, respectively. This nonroutine Benkelman beam deflection procedure was used to characterize the whole deflection basin that is needed in the structural evaluation methodology explained in the following sections.

The choice of 40 and 80 cm was not arbitrary. The goal was to choose one distance where the deflection would be about 50 percent of the maximum deflection. In Dominica this distance was between 30 and 40 cm,
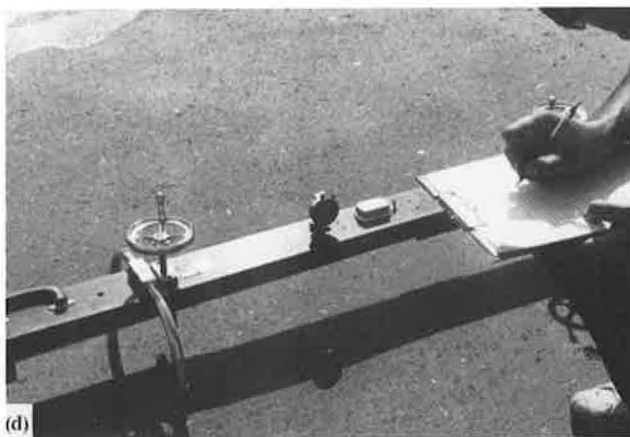

FIGURE 1   Benkelman beam operations in Dominica (Roseau-Hatton Garden Road).

```
100:REM NAME BENKE
    LMAN BEAM;DOMI
    NICA FEB./1983

105:REM  NAME"BBDO
    M/2"
110:REM  ASSUME WH
    EEL DIST.=3A
120:REM FEB./1983
200:GOSUB 5000:REM
    DATA
210:AC=A
220:INPUT "H/L=(10
    , INFINIT)";M$
230:CODE=3
240:IF M$="10"AND
    V3=.5THEN LET
    CODE=1
250:IF M$="10"AND
    V3=.4THEN LET
    CODE=2
255:REM CODE=1(H/L
    =10,V=.5)
260:IF CODE>1THEN
    GOTO 320
265:Y8=.620:M8=.18
    3:M9=.520:I9=.
    1614:ZZ=.1925/
    .1614
270:B=0:BB=1.6890:
    AA=.4065
280:IF DR/D0>.7
    THEN GOTO 900
290:B=2:BB=4.5663:
    AA=2.6947E-3
305:GOTO 900
310:REM CODE 2(H/L
    =10,V=.4)
320:IF CODE>2THEN
    GOTO 380
325:Y8=.602:M8=.19
    2:M9=.480:I9=.
    1689:ZZ=.1925/
    .1689
330:B=0:BB=1.8246:
    AA=.3804
340:IF DR/D0>.426
    THEN GOTO 900
350:B=3:BB=4.9903:
    AA=4.3795E-4
365:GOTO 900
370:REM CODE 3(H/L
    =INFINIT)
380:B=0:BB=1.7117:
    AA=.3210
390:Y8=.525:M8=.18
    0:M9=.440:I9=
    1925:ZZ=1.0
900:IF E3<>0THEN
    GOTO 1200
1000:REM  COMPUTE
     E3 HOGG
1040:R5=R*(1/AA^(
     1/BB)-B)/((1
     /AA*(D0/DR-1
     ))^(1/BB)-B
1050:LPRINT "R50
     CM=";INT (R5
     *10)/10
1060:AC=A
1070:L0=(Y8*R5+
     SQR ((Y8*R5)
     ^2-4*M8*AC*R
     5))/2
1080:IF AC/L0<.1
     THEN LET L0=
     (Y8-.1*M8)*R
     5
```

```
1085:LPRINT "L0
     CM=";INT (L0
     *10)/10
1087:WAIT
1090:AC=A
1100:SR=(1-M9*(AC
     /L0-.1))^-1:
     REM SR=S/S0
1110:IF SR<1THEN
     LET SR=1
1120:E3=(1+V3)*(3
     -4*V3)/2/(1-
     V3)*I9*PP/D0
     /SR/L0
1200:LPRINT "E0 K
     G/SQ.CM=";
     INT (E3)
1201:WAIT
1202:CBR=E3/CE
1203:LPRINT "CBR
     % =";INT (CB
     R*10)/10
1205:DS=E3*L0^3*2
     *(1-V3)/(1+V
     3)/(3-4*V3)
1208:WAIT
1210:REM  CENTER
     DEF BETWEEN
     WHEELS ;ULIT
     Z OFFSET DEF
     USED TO CAL
     CULATE D0
1220:AA=2*(1-V3)
1223:NN=100
1225:IF CODE=1
     THEN LET NN=
     10
1227:IF CODE=2
     THEN LET NN=
     10
1230:RR=1.5*A
1240:EC=2*E3
1250:DC=AA/EC/RR
1260:ZC=HC+.6*A*A
     /HC
1270:RC=SQR (ZC*Z
     C+RR*RR)
1280:DC=DC-(AA+(Z
     C/RC)^2)/RC/
     EC
1290:HE2=.9*HC*((
     EC/E3)^(1/3)
     )
1300:ZC2=HE2+.6*A
     *A/HE2
1310:RC2=SQR (ZC2
     *ZC2+RR*RR)
1320:DC=DC+(AA+(Z
     C2/RC2)^2)/R
     C2/E3
1330:ZC3=HE2+NN*L
     0+.6*A*A/(HE
     2+NN*L0)
1340:RC3=SQR (ZC3
     *ZC3+RR*RR)
1350:DC=DC-(AA+(Z
     C3/RC3)^2)/R
     C3/E3
1355:DC=DC*(1+V3)
     *PP/JT/2
1360:IF ABS (DC-D
     0)/D0<.01
     THEN GOTO 16
     10
1370:EC=EC*DC/D0
1380:GOTO 1250
```

```
1610:LPRINT "E* K
     G/SQ.CM=";
     INT (EC)
1620:WAIT
1890:REM  COMPUTE
     E1
1900:IF E1<>0THEN
     GOTO 2110
2000:REM  COMPUTE
     E1
2010:IF TRB=0THEN
     LET TRB=99.1
     3-26.35*.434
     3*LN (PEN)
2020:P1=20*TRB+50
     0*.4343*LN (
     PEN)-1951.55
2030:P1=P1/(TRB-5
     0*.4343*LN (
     PEN)+120.15)
2040:SB=1.157E-6*
     TS^-.368*2.7
     183^-P1*(TRB
     -TC)^5
2050:VG=(1-MB)/GS
     *(1-VA)
2060:VG=VG/(MB/GB
     +(1-MB)/GS)
2070:CV=VG/(1-VA)
2080:IF VA<.03
     THEN LET CV=
     CV/(.97+VA)
2090:N9=.83*.4343
     *LN (4E5/SB)
2100:E1=ATM*SB*(1
     +2.5/N9*CV/(
     1-CV))^N9
2110:LPRINT "E1 K
     G/SQ.CM=";
     INT (E1)
2120:WAIT
2390:REM  COMPUTE
     E2
2400:IF E2<>0THEN
     GOTO 2610
2500:REM  COMPUTE
     E2
2510:A8=H2/H1
2520:N8=1.0:REM N
     8=E1/E2
2530:REM E6=(E*/E
     1)TRIAL
2540:E6=A8^4+4*A8
     ^3*N8+6*A8^2
     *N8+4*A8*N8+
     N8^2
2550:E6=E6/N8/(A8
     +N8)/(A8+1)^
     3
2560:E7=EC/E1
2570:IF ABS (E6/E
     7-1)<.0001
     THEN GOTO 26
     00
2580:N8=N8*E6/E7
2590:GOTO 2540
2600:E2=E1/N8
2610:LPRINT "E2 K
     G/SQ.CM=";
     INT (E2)
2620:WAIT
2900:REM  COMPUTE
     DH
3000:HH=(EC*(HC^3
     )/3.0/E3)^(1
     /3)
```

```
3010:LPRINT "HEQ
     CM=";INT (HH
     )
3100:WAIT
3200:DH=(MJ*(CBR^
     -.55)-HH)/AE
3300:LPRINT "DH
     CM=";INT (DH
     *10)/10
4000:END
5000:REM DATA
5010:REM UNITS:CM
     .,KG.
5020:READ ATM
5030:DATA 1.0
5040:READ PP, A, TS
     , TC
5050:DATA 350./10
     .5,.010,27
5080:READ PEN, TRB
5090:DATA 50,55.0
5100:READ VA, GS
5110:DATA .035,2.
     65
5120:READ GB, MB
5130:DATA 1.04,.0
     6
5140:READ H1,H2,H
     C
5150:DATA 1.0,14.
     0,15.0
5160:READ V3, AE
5170:DATA .4,3.5
5180:READ E1, E2
5190:DATA 0000.,0
5200:READ E3, EC, C
     E:REM CE=E/C
     BR
5210:DATA 0,0,130
5220:READ D0, R, DR
     , MJ
5230:DATA 0.85E-1
     ,40,0.44E-1,
     76.20
5240:RETURN


     RUN    h/l = 10


R50 CM= 41.5
L0  CM= 21
E0 KG/SQ.CM= 447
CBR % = 3.4
E* KG/SQ.CM= 4596
E1 KG/SQ.CM= 22289
E2 KG/SQ.CM= 2367
HEQ CM= 22
DH  CM= 4



     RUN    h/l = ∞


R50 CM= 41.6
L0  CM= 17.3
E0 KG/SQ.CM= 594
CBR % = 4.5
E* KG/SQ.CM= 2773
E1 KG/SQ.CM= 22289
E2 KG/SQ.CM= 1128
HEQ CM= 17
DH  CM= 3.9
```
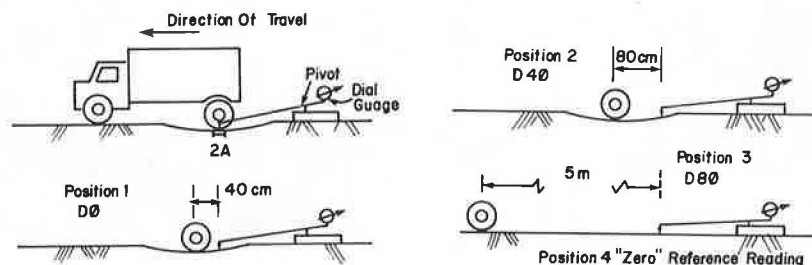
FIGURE 2 Computer program printouts.

FIGURE 3 Schematic of Benkelman beam deflection procedure.

and 40 was chosen for routine measurements. With little practice it is possible to measure the offset deflections without having to stop the moving truck. A team composed of the truck driver and his assistant, an experienced engineer and his assistant, and two traffic control men was able to measure 80 to 100 deflection basins, or about 10 km of road, in a typical working day. It is desirable that a small pickup truck is used to carry the men, the beam, and miscellaneous equipment.

DETERMINATION OF THE SUBGRADE MODULUS

In this section the subgrade modulus (EØ) and the California bearing ratio (CBR) are determined [see lines 1000 to 1023 of the program (Figure 2)]. The modulus of the subgrade EØ is determined by using the Hogg model (4-6) with a finite subgrade at a depth of H = 10 x LØ (see Figure 4) or at a depth of infinity,
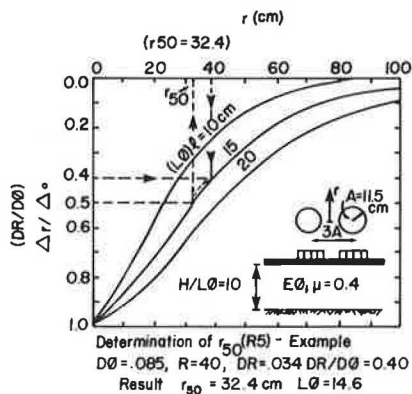
FIGURE 4 Deflection basins for Hogg model and Benkelman beam loading.

h = ∞. Figure 5 shows the computerized procedure that determines EØ from the interpretation of the deflection basin. This procedure is based on the following steps:

Step 1: Determination of r50 = R50;
Step 2: Determination of ℓ(LØ); ℓ(LØ) is the characteristic length (4-6);
Step 3: Determination of the ratio S_O (point load stiffness) to S (area load stiffness); and
Step 4: Calculation of EØ (E3).

Step 1: Determination of r50 (R5 or R50)

For purposes of this paper, r50 = R5, which is the offset distance R at which Δr/Δ0 = DR/DØ = 0.5. DØ and DR are the center and offset deflection, respectively.

The shape of the deflection bowl for point loading is described by the following equations:

$$(DØ/DR) - 1 = A[(R/ℓ) + B]^C \tag{1}$$

or

$$R = ℓ\left\{ (1/A)[(DØ/DR) - 1] \right\}^{1/C} - B \tag{2}$$

where A, B, and C are curve-fitting coefficients (see Table 1) and R is the distance offset of DR. For DR/DØ = 0.5,
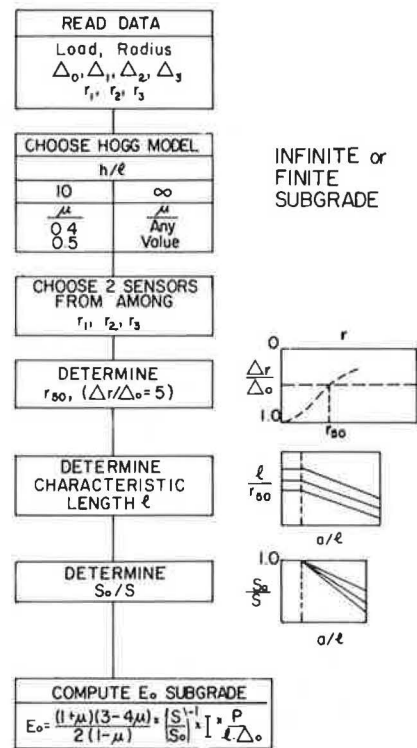
FIGURE 5 Determination of E subgrade from deflection measurements using Hogg model.

$$r50 = R5 = ℓ[(1/A)^{1/C} - B] \tag{3}$$

Thus Equations 2 and 3 give

$$R5 = R \left([(1/A)^{1/C} - B] / \left\{ (1/A) [(DØ/DR) - 1] \right\}^{1/C} - B \right) \tag{4}$$

The values for A, B, and C, as obtained for the Hogg model, are given in Table 1. For example, for μ = 0.4, h/LØ = 10, DØ = 0.085 cm, DR = 0.034 cm, R = 40 cm, and DR/DØ = 0.034/0.085 = 0.40, use Equation 4 to find R5 = 32.4 cm.

TABLE 1 Curve-Fitting Coefficients

H/LØ	DR/DØ	μ	A	B	C
H/LØ = ∞	Any value	Any value	1.3210	0	1.7117
10	>0.7	0.5	0.4065	0	1.689
10	>0.7	0.5	2.6947×10^{-3}	2	4.5663
10	>0.426	0.4	0.3804	0	1.8246
10	<0.426	0.4	4.3795×10^{-4}	3	4.9903

Figure 4 shows a graphical verification of the computerized solution. Enter the figure with DR/DØ = 0.40 and r = R = 40 cm. Draw a line parallel to the LØ lines until meeting the DR/DØ = 0.5 horizontal line. Read r50 on the horizontal axis (R5 = r50 = 32.4 m). The methodology for determining r50 is described in lines 1040 and 1050 of the computer program (see Figure 2).

Step 2: Determination of Characteristic length ℓ (LØ)

Figure 6 shows the theoretical relationships between ℓ/r50 and a/ℓ for different values of H/ℓ and μ [a(A)

is the radius of the contact area between the tire and the surface]. The equation shown in Figure 6 gives the same relationships in analytical form. Each different line in Figure 6 (1, 2, or 3) is described in the equation by different values of the parameters Y_0 and m for different values of μ and subgrade depth $H/L\emptyset = 10$ or ∞.
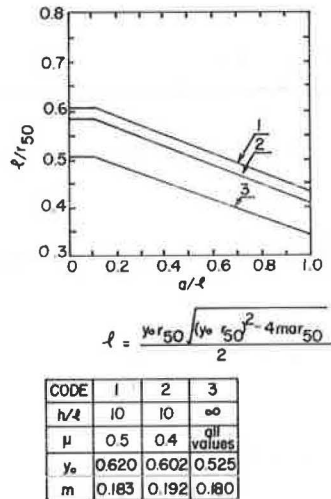

$$\ell = \frac{y_0 r_{50} \sqrt{(y_0 \ r_{50})^2 - 4mar_{50}}}{2}$$

CODE	1	2	3
h/ℓ	10	10	∞
μ	0.5	0.4	all values
y_0	0.620	0.602	0.525
m	0.183	0.192	0.180

FIGURE 6 Benkelman beam loading [$\ell = f(r_{50}, a/\ell)$].

The equation is used in the personal computer program to determine $\ell(L\emptyset)$. As an example, use the data that were used to determine r50: $H/L\emptyset = 10$, μ = 0.4, a(A) = 11.5 cm, $D\emptyset = 0.085$ cm, r50 = 32.4 cm, and PP = 3587 kg. Thus by using Code 2 in Figure 6, $\ell(L\emptyset)$ is

$$\ell = \{0.602 \times 32.4 + [(0.602 \times 32.4)^2 - 4 \times 0.192 \times 11.5 \times 32.4]^{1/2}\}/2.$$

$$\ell = 14.6 \text{ cm}.$$

The methodology for determining $\ell(L\emptyset)$ is described in lines 1070 and 1080 of the computer program.

Step 3: Determination of Ratio S_O/S

To develop numerical solutions of the subgrade modulus that are programmable in pocket computers, it is necessary to use this intermediate step. This step finds the theoretical relationship between point load (S_O) and area load (S) stiffnesses for a given ratio a/ℓ. This relationship is shown in Figure 7. Stiffness is defined as the ratio of the load to the deflection. The different lines (1, 2, and 3) in Figure 6 have an analytical expression that is also shown in Figure 7. A different value of the parameter m̄ is used for different values of $H/L\emptyset$ and μ. In the numerical example,

A/L = a/ℓ = 11.5/14.6 = 0.79;

thus

$$S_O/S = 1.0 - 0.48 (0.79 - 1.0) = 0.67.$$

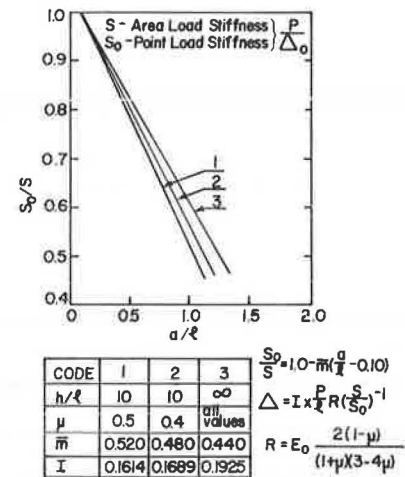The ratio S_O/S is determined in the computer program between lines 1100 and 1110.

CODE	1	2	3
h/ℓ	10	10	∞
μ	0.5	0.4	all values
m̄	0.520	0.480	0.440
I	0.1614	0.1689	0.1925

$$\frac{S_O}{S} = 1.0 - \bar{m}\left(\frac{a}{\ell} - 0.10\right)$$

$$\triangle = I \times \frac{P}{\ell} R \left(\frac{S}{S_O}\right)^{-1}$$

$$R = E_0 \frac{2(1-\mu)}{(1+\mu)(3-4\mu)}$$

FIGURE 7 Benkelman beam loading [$S_O/S = f(a/\ell)$].

Step 4: Calculation of EØ

EØ is finally found by using the following equation (see lines 1120 to 1200 of the program):

$$E\emptyset = \left\{ [(1 + \mu)(3 - 4\mu)]/2(1 - \mu) \right\} \times (I*PP/L\emptyset*D\emptyset) \times (S_o/S) \qquad (5)$$

where I is a fitting parameter that depends on $H/L\emptyset$ and μ (see table in Figure 7). For the data of the example,

$$E\emptyset = \{[(1 + 0.4)(3 - 4 \times 0.4)]/2(1 - 0.4)\}$$

$$\times [(0.1689 \times 3587)/(14.6 \times 0.085)]$$

$$\times 0.67 = 534 \text{ kg/cm}^2.$$

Determination of Subgrade CBR

The subgrade modulus can be used to calculate the CBR (4-6,8,9):

$$CBR = E\emptyset \text{ (in kg/cm}^2)/CE \qquad (6)$$

(see lines 1202 and 1203), where CE is an empirical factor that varies between 100 and 160 for in situ CBR between 2 and 30 (4). CE = 130 (see data lines 5200 to 5210) was used and found to be appropriate for the subgrade of the Roseau to Hatton Garden road in Dominica.
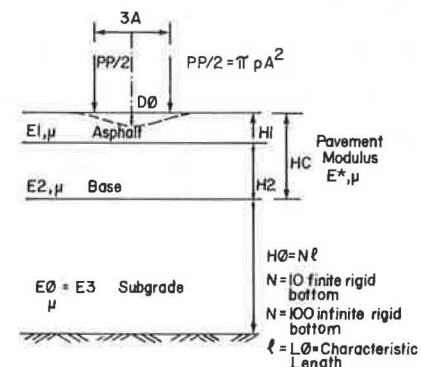

FIGURE 8 Determination of pavement modulus (E*).

DETERMINATION OF PAVEMENT MODULUS (E*)

The combined modulus E* of the asphalt concrete and the base layers with a combined thickness of HC = H1 + H2 (see Figure 8) is determined by using the Odemark-Ullidtz equations (10) for equivalent thickness (11). The equivalent thickness is determined according to the following equation:

$$HE = 0.9 \, HC \, (E^*/E\emptyset)^{1/3} \tag{7}$$

The relationship between the center deflection D∅ (between the dual wheels), the elastic modulus of the subgrade (E∅), and the pavement (E*) is given in the following equation:

$$D\emptyset = [(1 + \mu)(PP)/2\pi] \left[(1/E^*) \left([2(1 - \mu/r] - [1/R(1)] \left\{ 2(1 - \mu) + [Z(1)/R(1)]^2 \right\} \right) + (1/E\emptyset) \left([1/R(2)] \left\{ 2(1 - \mu) + [Z(2)/R(2)]^2 \right\} - [1/R(3)] \left\{ 2(1 - \mu) + [Z(3)/R(3)]^2 \right\} \right) \right] \tag{8}$$

where

$$r = 1.5A = 1.5a \tag{9}$$

$$Z(1) = HC + 0.6 \, (A^2)/HC \tag{9a}$$

$$R(1) = \left\{ [Z(1)]^2 + (1.5A)^2 \right\}^{1/2} \tag{9b}$$

$$Z(2) = HE + 0.6 \, (A^2)/HE \tag{9c}$$

$$HE = 0.9HC \, (E^*/E\emptyset)^{1/3} \tag{9d}$$

$$R(2) = \left\{ [Z(2)]^2 + (1.5A)^2 \right\}^{1/2} \tag{9e}$$

$$Z(3) = (HE + N\ell) + 0.6(A^2)/(HE + N\ell) \tag{9f}$$

$$R(3) = \left\{ [Z(3)]^2 + (1.5A)^2 \right\}^{1/2} \tag{9g}$$

N = 10 for rigid bottom at finite depth,
N = 100 for infinite subgrade, and
$PP = \pi A^2 p$ (p = tire pressure).

Equations 7, 8, and 9-9g are used iteratively to determine the pavement modulus E* for any given combination of subgrade modulus (E∅), pavement thickness (HC), load (PP), tire pressure (p), and center deflection (D∅). This calculation is done automatically by the computer (see lines 1210 to 1610 in Figure 2).

DETERMINATION OF ASPHALT MODULUS E1

Guidelines to determine the asphalt modulus are given, among other sources, in several reports (12-16). The Shell methodology (15,16) was found to be practical; it is implemented here for low-cost roads. According to this methodology, the stiffness of the bitumen (asphalt cement) can be calculated according to the following equation quoted from Ullidtz and Peattie (11):

$$SB = 1.157 \times 10^{-6} \times T_s^{-0.368} \times e^{-PI} \times (TRB - TC)^5 \tag{10}$$

where

SB = stiffness of bitumen (kg/cm²); the term stiffness is used to denote the modulus or instantaneous relationship between the stress and the strain, which corresponds to particular values of temperature and of loading;
T_s = time of loading (sec);
TRB = softening point, ring and ball (ASTM) of bitumen (°C);
TC = temperature of the bitumen (°C); and

PI = penetration index of the bitumen, i.e.,

$$PI = [20 \, (TRB) + 500 \, LOG \, (PEN) - 1{,}951.55]$$
$$\div \, [(TRB) - 50 \, LOG \, (PEN) + 120.15] \tag{11}$$

where PEN is the bituminous penetration at 25°C.

For the analysis of pavements, the properties of the bitumen in the road must be used. It may be convenient to recover bitumen from the road and measure its penetration directly. The following approximate relationship (11) has been found to apply to many road bitumens:

$$PEN \text{ in road} = 0.65 \times original \, PEN \tag{12}$$

It may also be convenient to measure TRB directly. Measurements of a wide range of road bitumens led to the development of the following empirical relationship (11):

$$TRB \, (°C) = 99.13 - 26.35 \times LOG \, (PEN) \tag{13}$$

Equation 10 gives reasonable results when the loading time is between 0.01 and 0.1 sec, the PI is between -1 and +1, and the TRB - TC is between 20° and 60°C. The detailed procedure to calculate PI and SB is given in the program (see lines 2000 to 2040). For example, if TS = 0.01 and TC = 27°C (data line 5050), and if field penetration PEN = 50 and TRB = 55°C (data line 5090), then using Equation 11 (lines 2020 and 2030 in the program) gives PI = 2.3 x 10^{-2} ≈ 0, and using Equation 10 (line 2040) gives SB ≈ 110 kg/cm².

The elastic modulus (E1) of the asphalt concrete (AC) mix is a function of the stiffness of the bitumen, the amount of mineral aggregate, and the air void percentage. E1 can be calculated according to the following equations (11):

$$E1 = SB \times \left\{ 1 + (2.5/N) \cdot [CV/(1 - CV)] \right\}^N \tag{14}$$

$$N = 0.83 \, LOG \, (4 \times 10^5/SB) \qquad SB \text{ in kg/cm}^2 \tag{14a}$$

$$CV = \begin{cases} VG/(1 - VA) & \text{when } VA \leqslant 0.03 \\ VG/[(1 - VA) \times (0.97 + VA)] & \text{when } VA > 0.03 \end{cases} \tag{14b}$$

$$VG = [(1 - MB)/GS] \times (1 - VA)/ \left\{ (MB/GB) + [(1 - MB)/GS] \right\} \tag{14c}$$

where

GS = specific gravity of the mineral aggregate (see lines 5100 and 5110, GS = 2.65),
VA = percentage of air voids (see lines 5100, 5110, VA = 0.035), and
GB and MB = specific gravity and percentage of the bitumen, respectively (see lines 5120 and 5130, GB = 1.04 and MB = 0.06).

For the specific case presented in Figure 2 (computer program), SB = 110.9, VG = 2.65, VA = 0.035, GB = 1.04, MB = 0.06, and E1 = 22 289 kg/cm².

The following concluding remarks summarize the determination of E1 (AC elastic modulus).

1. E1 is determined mainly from the engineering properties of the bitumen, the aggregate, and the AC mix.
2. E1 is used to determine E2 (granular material) based on the NDT methodology, as described in the following section. In the event that E1 is overestimated or underestimated, this will be reflected in the value of E2 in such a way that the total flexural stiffness (EH³) remains constant as backcalculated from the NDT data.
3. The methodology presented herein is applica-

ble to uncracked, sound AC layers greater than 1 in. thick. Cracked or thin asphalt should be considered as part of the granular layer.

DETERMINATION OF BASE MODULUS E2

The modulus of the base layer is determined according to Nijboer's equation (Equation 15), which is based on the theory of strength of materials (16):

$$E*/E1 = [H2/H1)^4 + 4(H2/H1)^3(E1/E2) + 6(H2/H1)^2(E1/E2) + 4(H2/H1)(E1/E2) + (E1/E2)^2]/\{ (E1/E2)[(H2/H1) + (E1/E2)] [(H2/H1) + 1]^3\} \tag{15}$$

Equation 15 is based on the assumption that the flexural rigidity (EI) of the two layers H1 and H2 is equal to the EI of the composite pavement E* and HC, or

$$EI (E1, H1 and E2, H2) = EI (E*, HC).$$

It is also assumed that there is full friction between the asphalt and the base layers. The input data are

H1 = asphalt layer thickness,
E1 = asphalt modulus,
H2 = base thickness,
E* = composite pavement modulus of the asphalt and base materials, and
HC = H1 + H2, which is the total pavement thickness of asphalt and base materials.

The only unknown is the elastic modulus of the granular material (E2), which is determined iteratively by using the personal computer (see lines 2500 to 2610 in the computer program).

DETERMINATION OF OVERLAY THICKNESS DH

The required overlay thickness DH' is determined by using the following procedure:

$$DH' = H - HEQ \tag{16}$$

where DH' is the required additional thickness of gravel material (subbase or base), and H is the required total pavement thickness, subbase (CBR = 30) + base (CBR = 80) + thin layer of asphalt (usually less than 2 in.). H can be determined by using any

FIGURE 9 Thickness design curves for Roseau-Hatton Garden Road (21).

pavement design methodology for low-volume roads (17-21) that presents the relationship between the subgrade CBR, the projected traffic loading, and H. Figure 9 (21) shows the thickness design curves used for the rehabilitation program of the Roseau-Hatton Garden road in Dominica; the curves are based on the Transport and Road Research Laboratory (TRRL) method (21). As an example, the projected traffic loading of the road section from Pont Casse to Hatton Garden is 16,000 equivalent axle loads (EALs). In this case, the required thickness for CBR = 6 is H = 10.5 in. The mathematical relationship between H and CBR for the Roseau-Hatton Garden road [TRRL method (21)] is given in the following equation (see also Figure 9):

$$H = (MJ)*(CBR)^{-0.59} \tag{17}$$

where H is the required thickness (in.) and MJ is a constant for a given traffic loading:

Road Section (in Dominica)	N18	MJ
Roseau-Hillsborough Bridge	16,000	30.0
Hillsborough Bridge-Pont Casse	36,000	32.0
Pont Casse-Hatton Garden	45,000	33.0

The existing pavement is a nonuniform granular waterbound macadam covered by a thin asphalt layer. The thickness of the granular material varies between 4 and 8 in., and the asphalt thickness is less than 1 in. The elastic modulus of the pavement (E*) varies mainly between 0.5 to 10 times the EØ of the subgrade. The lower values (E* = 0.5 to 2EØ) generally correspond to failed-to-poor sections.

For cases such as Dominica, where there is a large variability between the back-calculated E*/EØ ratios, it is necessary to bring the different sections to the same comparative basis. This is done by introducing the flexural stiffness concept. Flexural stiffness is a function of the thickness of the pavement and its modulus of elasticity and Poisson's ratio. Poisson's ratio is assumed to be constant for low-cost roads and to vary between 0.35 and 0.45. If the existing pavement with elastic modulus E* and thickness HC is equivalent to a new pavement with elastic modulus Ep and thickness HEQ, the following relationship between the flexural strength of the existing and the new pavement holds:

$$(E*) (HC)^3 = (Ep) (HEQ)^3 \tag{18}$$

HEQ in Equations 16 and 18 is the equivalent thickness of the new pavement.

The pavement structure of low-cost roads is constructed mainly from granular material such as subbase or base. The thickness of the AC is usually less than 2 in. In these cases the elastic modulus of the pavement structure (Ep) is derived from the elastic modulus of the granular material and must lie between 2 and 4 times EØ (11). In Dominica, the relationship of Ep = 3EØ was used to determine HEQ and DH', as defined in Equations 16 and 18. In simpler terms, if E* is found equal to 3 times EØ, then HEQ is equal to HC. Finally, if E* is greater than 3 times EØ, then HEQ is greater than HC. The value of HEQ gives credit to the flexural strength of the existing pavement.

DH' determined according to Equations 16-18 is in inches of granular material. When asphalt is used to overlay the pavement, DH' should be divided by an equivalency factor. This factor varies mainly between 1.5 and 4.0. According to the FAA (22), 1 in. of AC is equivalent to 1.5 in. of high quality base. According to the Asphalt Institute (3) and the Transportation Research Board (21), 1 in. of asphalt might be equivalent to 2 to 3 in. of granular mate-
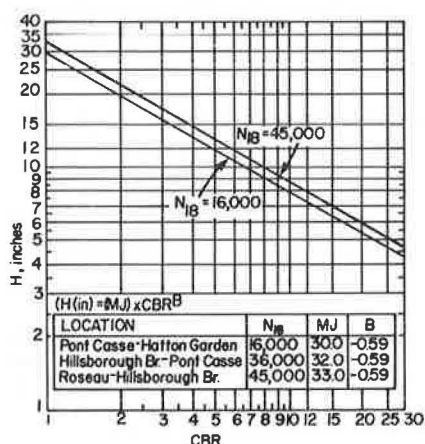
rial. The AASHTO (22) practice is that 1 in. of asphalt is equivalent to 3.2 in. of unstabilized base course or 4 in. of subbase. In the case of Dominica, it was found that the AC produced from the local aggregates has high strength and durability values. The Marshall stability is more than 2,000 lb, flow is 10 to 15, and immersion compression retained greater than 85 percent. Therefore, for this project in Dominica, where a high quality AC is designed, 1 in. of asphalt is equivalent to 3.5 in. of granular material, or the DH in thickness of AC is as follows:

$$DH = (H - HEQ)/3.5 = [(MJ)*(CBR)^{-0.59} - HEQ]/3.5 \qquad (19)$$

The methodology for determining DH is described between lines 2900 and 3300 of the computer program.

SUMMARY

The computerized rational methodology of road rehabilitation presented in this paper was implemented in upgrading 50 km of a low-volume road in Dominica. A pocket computer (Sharp PC-1500) with 8-K RAM was used in the field to determine the minimum required AC overlay to carry 16,000 to 45,000 EALs. The following engineering parameters were calculated (see calculation example in Figure 2):

1. R50 (r50), the offset distance R at which the deflection ratio DR/DØ = 0.5 (see Figure 4);
2. LØ(ℓ), the characteristic length (Hogg model);
3. EØ, the subgrade elastic modulus;
4. CBR, the subgrade CBR;
5. E*, the combined modulus of the asphalt and the base layers;
6. E1 and E2, the modulus of the asphalt and the base, respectively;
7. HEQ, the equivalent thickness of a new pavement with E* = 3EØ; and
8. DH, the required AC overlay thickness.

The calculations of the AC overlay are done with a finite subgrade at a depth of h = 10ℓ (see Figure 4) or at infinity, h = ∞. The finite subgrade case is more often implemented and always results in lower values of the subgrade modulus and higher values of the pavement modulus in comparison with the infinite subgrade model. The AC overlay thick- ness DH is not sensitive to the subgrade depth. The use of the computer enables all the calculations, including the overlay thickness, to be completed in about 1 min. Therefore the rehabilitation or the overlay design can be completed while conducting the NDT. In Dominica, the NDT and the strengthening design of 50 km of rural roads were carried out simultaneously and completed in 1 week.

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