

CONCRETE PAVEMENT LAYER MODULI BASED ON STABLE DEFLECTION

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Microcomputer methods are widely used to backcalculate pavement layer moduli from deflections measured on the pavement surface. To increase the precision of the backcalculated moduli, a new, layer moduli backcalculation method based on the stable deflection was developed for concrete pavements. This stable deflection is defined as being independent of the slab modulus. Thus, it is a critical parameter for uniquely determining the foundation reaction modulus and for further backcalculating the slab modulus.

This procedure was used to evaluate the structural condition of concrete pavement in a working airport, and the usefulness of the method was verified as a result.

Key Words: concrete pavement, structural evaluation, stable deflection, FWD, backcalculation, layer modulus

1. INTRODUCTION

Nondestructive testing (NDT) has become widely accepted as an increasingly cost-effective tool for evaluating the structural condition of airport and highway pavements and is now an interesting and active research area in the world. Estimations of the pavement layer moduli from deflections measured by NDT is a major problem, and numerous backcalculation methods have been developed. These backcalculation methods are divided into four categories,¹⁾ i.e.,

- (a) traditional methods based on graphs and/or tables,
- (b) microcomputer methods, such as ELCON, ILLI-BACK for rigid pavements, and ISSEM4, MODCOM3, MODULUS and WESDEF for flexible pavements,
- (c) system identification methods, and
- (d) impulse methods for near-field measurements.

Of these, microcomputer methods are discussed here. In fact, the basic principles used in the various layer moduli backcalculation methods are similar; i.e., they attempt to find a set of moduli that minimize the difference between the measured deflection basin

shape and the shape calculated using known layer moduli. The typical objective function used in moduli backcalculation is as follows:²⁾

$$\text{Min } e^2 = \sum_{i=1}^N (D_{Mi} - D_{Ci})^2 \quad (1)$$

where,

D_{Mi}, D_{Ci} : the measured and calculated deflection at i th sensor, respectively, and

N : the total number of sensors.

Because the layer moduli significantly influence the shape of the deflection basin, the set of moduli obtained through Eq. (1) is usually not unique. This often results in greater errors in the backcalculated moduli.¹⁾

Many refined algorithms have been developed to improve the uniqueness of the solution and to increase the precision of the backcalculated moduli. Two methods are typical, i.e. the use of different weighting factors for the various sensors, and the use of a range of moduli for each pavement material.

Thus, the layer moduli backcalculation process becomes the following optimization process with the constraint of layer moduli:

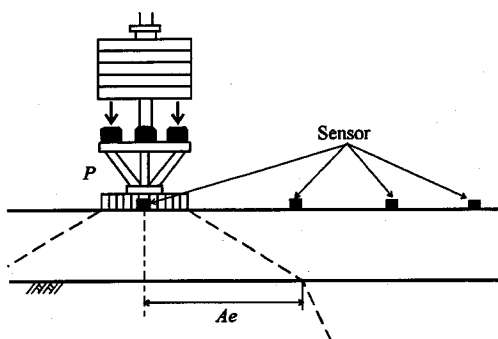


Fig. 1 Stress zone in pavement structure

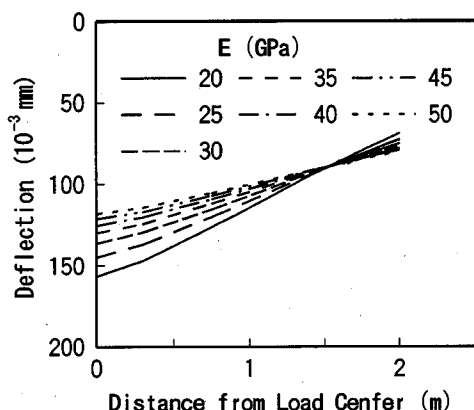


Fig. 2 Stable deflection within a narrow range

$$\text{Min } e^2 = \sum_{i=1}^N W_i \cdot (D_M - D_C)^2$$

$$E_j \leq E_{j \max}$$

$$E_j \geq E_{j \min}$$
(2)

where,

W_i : a weighting factor of i th sensor,
 $E_j, E_{j \min}, E_{j \max}$: backcalculated, possible minimum and maximum modulus of j th layer, respectively.

Even with these techniques, moduli backcalculation is still a laborious process that requires a high degree of skill. The results are known to be highly dependent on the individuals doing the backcalculation.³⁾

This paper presents a new, layer moduli backcalculation method for concrete pavement that is based on a stable deflection. The structural condition

of concrete pavement in a working airport is then evaluated.

2. FEATURES OF CONCRETE PAVEMENT DEFLECTION BASINS

The effect of a pavement layer under load is shown in Fig. 1. The load applied to the surface is distributed through the thickness of the pavement system. The stress distribution in the pavement is clearly related to the layer moduli, i.e. the stress distribution area increases with increasing modulus. Surface deflections obtained at or beyond the distance A_e in the figure are due only to stresses, and hence deformations, within the foundation itself,²⁾ while surface deflections near the load are mainly dependent on the surface modulus.

The deflection basins of concrete pavement, including deflections far away from the load, are dependent on both the slab (elastic) modulus and the foundation reaction modulus. That is, the smaller the foundation reaction modulus is, the greater the deflections will be both at the load center and at points away from the load. A higher slab modulus produces a flatter deflection basin; i.e., the deflections near load center are relatively small, while the deflections far away from the load are relatively large. Conversely, a lower slab modulus results in a deeper deflection basin; i.e., the deflections near load center are relatively large, while the deflections far away from the load are relatively small. Thus, an intersection between deflection basin shapes with high and low slab moduli must exist at which the deflection is independent of slab modulus, as shown Fig. 2.

In order to prove the existence of the point at which the pavement deflection is independent of slab modulus, the authors used the thick plate theory to analyze numerous deflection basins of concrete pavement structures. As shown in the example given in Fig. 2, the deflections at a particular radius (about 1.55 m from the load center) are almost unchanged. The deflection basins intersect within a narrow range that is less than 50 mm wide even for different slab moduli. In other words, a relatively stable point exists on the deflection basin at which the deflection remains nearly unchanged for varying slab moduli. The deflection at any other point is dependent on both the slab modulus and the foundation reaction modulus. Thus, a deflection that is independent of the slab modulus is critical for uniquely determining the foundation reaction modulus and further backcalculating the slab modulus. This deflection is defined as the stable deflection D_c at the distance from the load center R_c .

Table 1 Concrete pavement parameters used in deflection analysis

Slab Thickness (mm)	200, 250, 300, 350, 400, 450
Slab Modulus (GPa)	20, 25, 30, 35, 40, 45, 50
Foundation Reaction Modulus (MPa/m)	50, 100, 150, 200
Slab Dimension (m)	4 x 4, 5 x 5, 7.5 x 7.5
Load Plate Diameter (mm)	300, 450

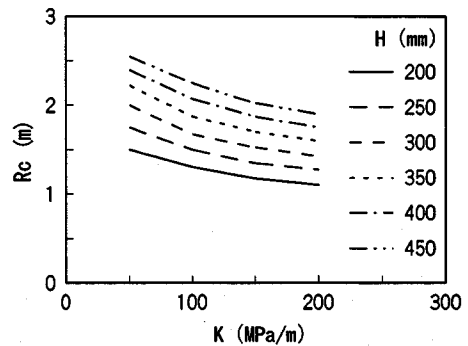


Fig. 3 Relationship between K , H , and R_c

Table 2 Calculated R_c and D_c

H (mm)	K (MPa/m)	4 m x 4 m Slab		5 m x 5 m Slab		7.5 m x 7.5 m Slab	
		R_c (m)	D_c (10^{-3} mm)	R_c (m)	D_c (10^{-3} mm)	R_c (m)	D_c (10^{-3} mm)
200	50	1.375	104.92	1.475	90.27	1.500	182.64
	100	1.225	65.45	1.225	63.49	1.300	120.50
	150	1.125	51.25	1.125	49.29	1.175	97.91
	200	1.025	45.58	1.050	41.82	1.100	83.53
250	50	1.475	93.07	1.675	70.46	1.750	138.94
	100	1.375	52.27	1.475	44.93	1.500	91.77
	150	1.275	40.91	1.325	36.58	1.350	74.46
	200	1.200	33.84	1.225	31.56	1.275	62.34
300	50	1.500	90.91	1.775	63.21	2.000	108.97
	100	1.450	47.58	1.625	37.20	1.675	74.95
	150	1.400	28.81	1.500	28.90	1.525	59.18
	200	1.350	26.89	1.400	24.67	1.425	50.28
350	50	1.525	88.32	1.850	59.20	2.225	89.17
	100	1.500	45.37	1.725	33.13	1.875	61.07
	150	1.450	31.62	1.625	24.70	1.700	48.50
	200	1.425	24.36	1.550	20.26	1.600	40.52
400	50	1.550	88.42	1.900	57.34	2.400	76.87
	100	1.525	45.65	1.800	30.37	2.075	50.64
	150	1.500	30.17	1.725	22.01	1.875	41.56
	200	1.475	23.07	1.675	17.41	1.750	34.41
450	50	1.550	88.42	1.925	56.72	2.550	68.33
	100	1.525	44.58	1.850	29.49	2.250	43.38
	150	1.500	-	1.800	20.43	2.025	35.62
	200	1.475	23.02	1.750	16.03	1.900	29.61

Load Diameter: 300 mm for 4 x 4 and 5 x 5 Slab, and 450 mm for 7.5 x 7.5 Slab
Load Intensity: 1 Mpa

3. ANALYSIS OF STABLE DEFLECTION

The position (R_c) and magnitude (D_c) of the stable deflection are useful in layer moduli backcalculation. The authors consider the slab modulus and the foundation reaction modulus as the dominant parameters and addressed deflection basins at the slab center, although many factors have a significant influence.

(1) Analysis Condition

Considering both pavement structures and material characteristics commonly used in airport and

highway construction, the deflection basins were analyzed for concrete pavements having the various structural parameters shown in **Table 1**. The deflection basins with all combinations of the parameters shown in this table were obtained by calculating the deflection at 50 mm intervals.

(2) Position of Stable Deflection

The practical determination of the stable deflection used the point where the change of deflections is within 1.5 % for slab moduli of 20 and 50 GPa. Based on this principle, R_c is determined from the deflection basin data, as listed in **Table 2**.

Table 3 Range of R_c

Slab Dimension (m x m)	Slab Thickness (mm)					
	200	250	300	350	400	450
4 x 4	1.00-1.40	1.20-1.50	1.30-1.50	1.40-1.55	1.45-1.55	1.45-1.55
5 x 5	1.05-1.50	1.20-1.70	1.40-1.80	1.50-1.90	1.65-1.90	1.75-1.95
7.5 x 7.5	1.10-1.50	1.25-1.75	1.40-2.05	1.60-2.25	1.75-2.40	1.90-2.55

(unit: m)

Table 4 Coefficients in Eq. (3)

Coefficient	4 x 4 Slab	5 x 5 Slab	7.5 x 7.5 Slab
a_0	2.0565E-01	-5.2959E+00	1.5264E+00
a_1	1.5687E-02	7.8658E-02	-7.8229E-03
a_2	-6.9500E-05	-3.2357E-04	6.3783E-05
a_3	1.3790E-07	5.9435E-07	-1.2706E-07
a_4	-1.0200E-10	-4.0867E-10	8.3667E-11
b_0	-6.5407E-03	-3.7467E-03	-8.0339E-03
b_1	2.9800E-05	7.0798E-06	8.4677E-05
b_2	-3.5614E-08		-4.3134E-07
b_3			9.2118E-10
b_4			-6.9953E-13

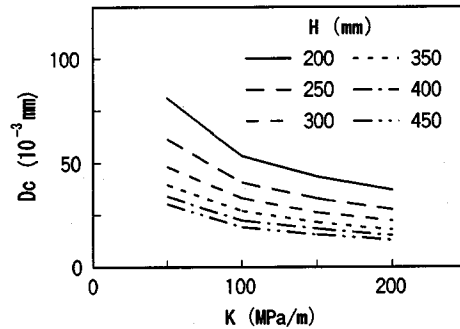


Fig. 4 Relationship between K , H , and D_c

As can be seen from **Fig. 3**, which was plotted using data for a 7.5 m x 7.5 m slab, R_c decreases with increasing foundation reaction modulus and increases with increasing slab thickness. The range of R_c for various pavement structural parameters is listed in **Table 3**.

The relationships between R_c (m), the foundation reaction modulus K (MPa/m) and the slab thickness H (mm) can be regressed using the data in **Table 2** as follows:

$$R_c = A \cdot \exp(B \cdot K)$$

$$A = a_0 + a_1 \cdot H + a_2 \cdot H^2 + a_3 \cdot H^3 + a_4 \cdot H^4 \quad (3)$$

$$B = b_0 + b_1 \cdot H + b_2 \cdot H^2 + b_3 \cdot H^3 + b_4 \cdot H^4$$

Coefficients a_0 through a_4 and b_0 through b_4 are shown in **Table 4**.

(3) Stable Deflection

Although the stable deflection is nearly independent of the slab modulus, it decreases with increases in either K or H . This is shown in **Fig. 4**, which was plotted using data for the 7.5 m x 7.5 m slab. The following relationships were obtained based on these data (P denotes the load in N):

$$D_c = P \cdot C \cdot (K/9.80665)^p$$

$$C = c_0 + c_1 \cdot H + c_2 \cdot H^2 + c_3 \cdot H^3 + c_4 \cdot H^4 \quad (4)$$

$$D = d_0 + d_1 \cdot H + d_2 \cdot H^2 + d_3 \cdot H^3 + d_4 \cdot H^4$$

Coefficients c_0 through c_4 and d_0 through d_4 are shown in **Table 5**. For 7.5 m x 7.5 m slab, C is expressed as $C = 0.0016955H^{-1.1837}$.

Table 5 Coefficients in Eq. (4)

Coefficient	4 x 4 Slab	5 x 5 Slab	7.5 x 7.5 Slab
c_0	2.7716E-03	3.3377E-02	
c_1	-8.5124E-06	-3.5470E-04	
c_2	9.8472E-08	1.4856E-06	
c_3	-1.4023E-10	-2.6930E-09	
c_4		1.8128E-12	
d_0	4.5680E-01	-1.4966E+00	-9.4451E-01
d_1	-7.0327E-03	1.1075E-02	5.0817E-03
d_2	8.5987E-06	-3.9871E-05	-2.5058E-05
d_3		4.0313E-08	5.5122E-08
d_4			-4.6100E-11

Because the slab thickness is known when backcalculating the layer moduli, D_c is only dependent on the foundation reaction modulus. Therefore, K can be uniquely determined after D_c is determined by backcalculating from the measured deflection basin. The slab modulus can then be backcalculated using any deflection, such as the one at the load center.

4. BACKCALCULATION PROCEDURE FOR LAYER MODULI OF CONCRETE PAVEMENT

(1) Determination of K

A trial and error procedure is used to determine the foundation reaction modulus K . An example is given below.

In order to simplify the example, Fig. 5 is also plotted using the data in Figs. 3 and 4. An example of the deflection basin for a concrete pavement with a slab of 7.5 m by 7.5 m by 350 mm thick is listed in Table 6.

From Table 3, the stable deflection (R_c) is assumed to be located between 1.6 and 2.25 m. Therefore,

- Step 1: Assume 1.9 m as R_c ($= R_c'$),
- Step 2: Interpolate D_c at R_c' based on measured deflection in Table 6,
- Step 3: Calculate R_c from Fig. 5 based on D_c ,
- Step 4: Calculate difference between R_c and R_c' . If the difference is not sufficiently small, go to Step 5, otherwise go to Step 6,
- Step 5: Let $R_c' = R_c$, and go to Step 2, and
- Step 6: Calculate K based on R_c .

In this example, the calculated K is 96.1 MPa/m. Because the slab dimensions, slab thickness and K are given, R_c and D_c are unique. Therefore, the converged foundation reaction modulus is also unique.

(2) Flowchart for Layer Moduli Backcalculation

Two steps are included in the layer moduli backcalculation for concrete pavement, i.e. the determination of the foundation reaction modulus and the backcalculation of the slab modulus, as shown in Fig. 6.

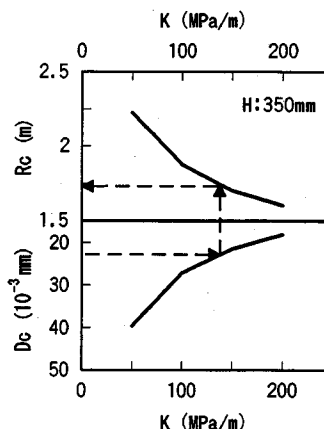


Fig. 5 Determination procedure of K

Table 6 Example of concrete pavement deflection basin

Sensor No.	1	2	3	4	5	6	7
Distance from Load Center (mm)	0	300	450	600	900	1500	2500
Deflection (10^{-3} mm)	241	225	209	194	166	95	45

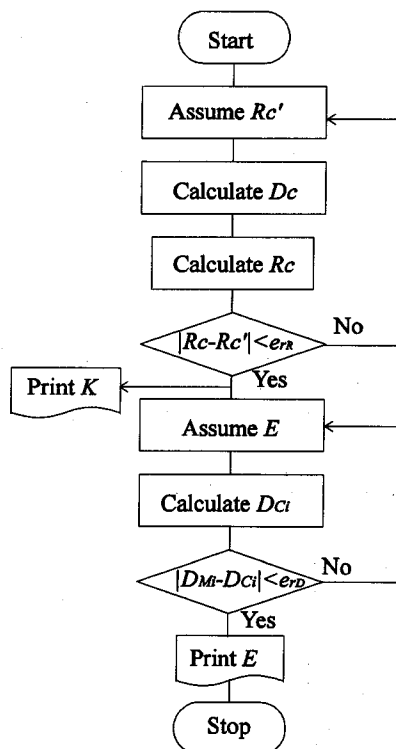


Fig. 6 Flowchart of layer moduli backcalculation

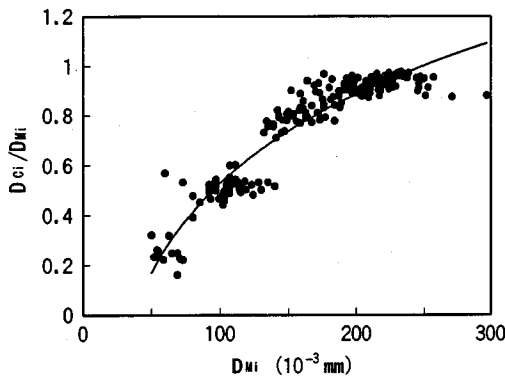


Fig. 7 Adjustment factor for FWD deflections

5. APPLICATION TO ACTUAL AIRPORT CONCRETE PAVEMENT

(1) Outline

The airport concrete pavement analyzed in this paper was constructed about 5 years ago and includes two pavement structures, i.e., one with dimensions of 7.5 m by 7.5 m by 350 mm thick, and another with dimensions of 5 m by 5 m by 200 mm thick. The foundation reaction modulus used in the design was 70 MPa/m, and the slab modulus used in design was 35 GPa. The FWD tests were made in June 1994.

(2) Data Adjustment

A comparison between the calculated and measured deflection basins shows significant differences, where the measured deflection basins are much flatter than the calculated ones. This may be caused by assuming the subgrade acts as a Winkler foundation when calculating the deflection basin. The foundation reaction modulus, however, should be obtained from the concrete pavement evaluation because this foundation model was used in the concrete pavement structural design.

The authors attempted to adjust the measured data to make use of this procedure and to determine the possible stable deflection points from the measured deflection basin data. Using the possible stable deflection points shown in Table 2, the following data adjustment factor was obtained, as shown in Fig. 7.

$$CF = D_{ci} / D_{mi} \\ = -1.901 + 1.191 \cdot \log(D_{mi}) \quad (5)$$

where,

i : sensor No. (= 3, 4, ..., 7),

Table 7 Adjustment of measured deflection basin

Sensor No.	1	2	3	4	5	6	7
Measured Deflection (10^{-3} mm)	285	273	268	256	229	190	135
Adjusted Deflection (10^{-3} mm)	285	273	268	256	219	163	92

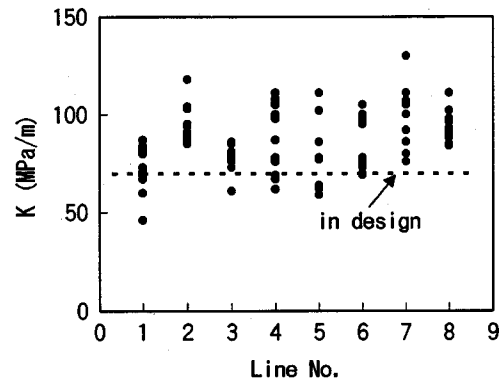


Fig. 8 Comparison between backcalculated K and K used in design

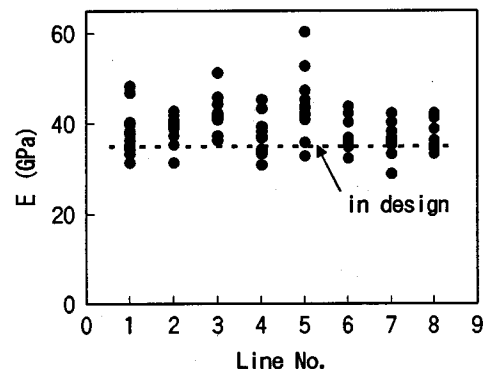


Fig. 9 Comparison between backcalculated E_c and E_c used in design

D_{ci}, D_{mi} : calculated, measured deflection in 1/1000 mm, respectively.

If CF calculated from Eq. (5) is larger than unity, then let $CF = 1$.

Before backcalculating the concrete pavement layer moduli, the measured deflection basin should be adjusted using Eq. (5) as shown in Table 7.

(3) Backcalculated Layer Moduli

The backcalculated moduli are described in Figs. 8 and 9, which compare the backcalculated modulus with that used in the design. Obtained moduli coincide well with those used in the design.

sensors should be placed between 1.4 m and 2.5 m. If the estimated foundation reaction modulus is less than 50 MPa/m for a slab thickness greater than 450 mm, deflections should be measured at distances greater than 2.5 m.

6. CONCLUDING REMARKS

Although numerous layer moduli backcalculation methods have been developed for airport and highway concrete pavement, the range of backcalculated moduli is still large. A stable deflection was found in concrete pavements, and based on the new findings, a new, layer moduli backcalculation method was developed for the nondestructive evaluation of concrete pavements. This was used for the nondestructive evaluation of a working airport concrete pavement, and the estimated slab modulus and the foundation reaction modulus were comparable to those used in the design.

For the nondestructive tests made in a concrete pavement with dimensions of 7.5 m by 7.5 m and more than 300 mm thick, it was determined that more

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- 3) Strategic highway research program: Sharp's layer moduli backcalculation procedure, *SHRP-P-655*, National research council, 1993.

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不変たわみ量に基づくコンクリート舗装の変形係数

孫 立軍・八谷好高・姚 祖康

舗装表面でのたわみから舗装構成層の弾性係数を逆解析する場合にはコンピュータを用いる方法が多用されている。コンクリート舗装の場合の解析精度を向上させるために、不変たわみ量に基づく方法が開発された。このたわみ量はコンクリート版の弾性係数に依存しないものであるから、路床支持力係数、さらにはコンクリート版の弾性係数も唯一解として得られる。

この方法は、供用中の空港コンクリート舗装の構造評価に使用され、結果としてその有用性が確認された。

UDEC 3DEC

個別要素法(DEM)プログラム

個別要素法(離散要素法)は、1971年にDr. P. Cundallが発表した不連続体数値解析手法であり、岩盤や地盤をブロックや土粒子の要素の集合体と考え、個々の要素が隣接要素から受ける力により運動方程式にもとづき挙動する様子を時間差分式にて時刻繰返し計算する手法です。個別要素法は不連続力学の中心手法として位置づけ

られ、岩盤・地盤の崩落や安定性の解析、大深度地下空間、核廃棄物地下処理、鉱物資源開発等のプロジェクトおよび粒状体力学(粉体工学)の分野で有力な解析手段となっています。現在UDEC、3DECは全世界の研究機関・企業で標準コードとして広く使用されています。

オプション

■ Barton-Bandisモデル

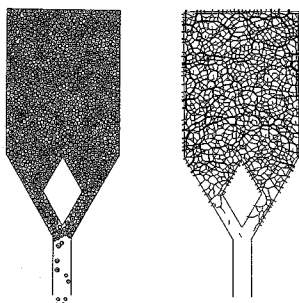
適用分野

- 粒状物質の挙動解析
- 鉱山採掘等 掘削解析
- 地震応答解析
- ジョイント内流れ解析
(浸透連成: UDEC)
- 核廃棄物の熱応力解析
(熱連成: UDEC)

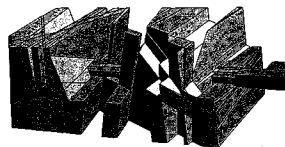
■販売条件

UDEC・3DEC・FLAC

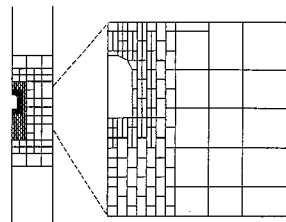
- ◆ EWS (SUN-SPARC)
- ◆ IBM-PC/AT及び互換機
- ◆ UDECはソースコードで提供します。
- ◆ 3DEC・FLACはロードモジュールで提供します。



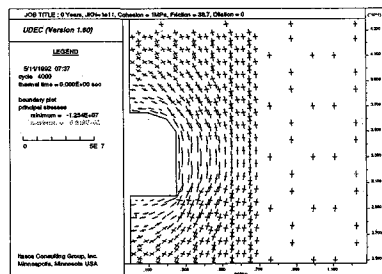
ホッパー内粒状体挙動解析



亀裂性岩盤の3次元掘削解析



核廃棄物地中処理影響解析



FLAC

有限差分法(FDM)プログラム

FLACは個別要素法コードUDEC、3DECを発表したDr. P. Cundallが同様の有限差分ロジックを用いて連続体の塑性大変形の解析するために開発したコードで、現在、全世界で数多く使用されています。有限差分法は、地盤、岩盤を有限な領域内で離散化し、運動方程式と構成則を差

分方程式として解析するもので、有限要素法に比べ非線形大歪が扱えることで大きな優位性を持っています。

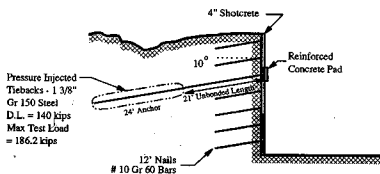
FLACは小～大歪 非線形、動的・静的挙動を始めとし、豊富な機能 オプションを備えたPC、ワークステーション用の地盤解析コードです。

オプション

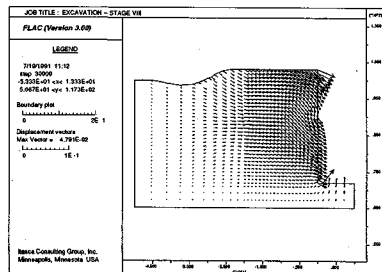
- ダイナミック解析モデル
- クリープ解析モデル
- 熱解析モデル

適用分野

- 斜面・盛土の設計、安定解析
- 浅・深基礎設計
- アースダム、コンクリートダムの設計
- トンネルの設計
- 核廃棄物貯蔵解析
- 液状化解析



日本技術開発株式会社



パソコン用、準3次元広域地下水変動解析プログラム

PC/UNISSF Ver.3.0 for Windows

“PC/UNISSF Ver.3.0”は、すでに汎用機やEWSで実績のある準3次元広域地下水変動解析プログラム、UNISSF(V-2)に強力なプリ・ポスト処理プログラムを付加し、Windows版として新登場しました。このプリ・ポストプログラムは、マウスを使ったメニュー形式の導入、画面上での入出力等の機能により、すぐれた操作性をもたらします。

新登場!

プログラムの特徴 (☆印は新機能)

■プリ処理

- ☆モデル作成のためのメッシュジェネレート機能
- ★地層データ、初期水位データ等の自動発生機能
- ☆モデル図を参照しながら、境界条件等各種データの入力、修正が可能
- ☆マウス入力とメニュー形式による操作性の向上

■ 解析機能

- ☆汎用機、EWS版と同一機能（順解析）、同一データフォーマット
- ☆約3000～10000節点までのモデルが解析可能
- ★降雨・揚水井・浸出面の取り扱いが可能
- ★水位・流量の経時変化
- ★境界条件の変更、材質の変更
- ★掘削機能・簡易漏水機能
- ★初期定常計算・非定常計算・最終定常計算

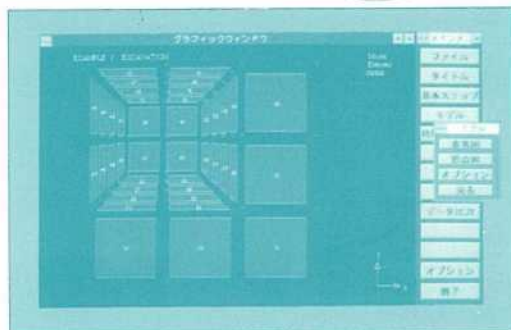
■ポスト処理

- ☆線画に加えて画面塗りつぶし処理が可能
- ☆水位の時間変化が簡単にグラフ化可能
- ☆マウス入力とメニュー形式による操作性の大幅な向上

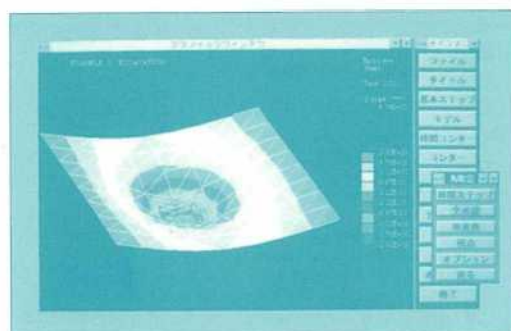
動作環境

Windows Ver.3.1
CPU: 80386 以上 (推奨 80486DX 33MHz以上)
RAM: 8MB 以上
ハードディスク容量: 10MB以上

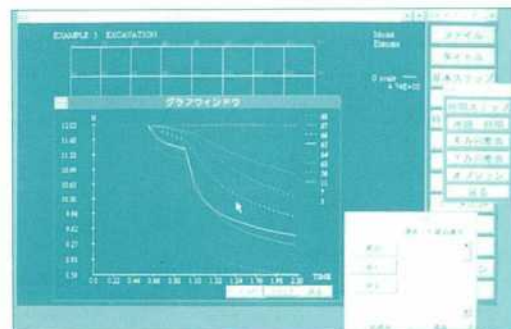
- ・UNISSFは情報処理振興事業会の委託を受けて当社で開発したプログラムです。
- ・Windowsは米国マイクロソフト社の商標です。



【モデル図】



【全水頭コンター】



【水位変化グラフ】

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