ANALYSIS OF THEORETICAL BASIS FOR ASSESSING THE BEARING CAPACITY OF AIRPORT CEMENT CONCRETE PAVEMENT IN VIETNAM BY THE DYNAMIC DEFLECTION EQUIPMENT

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Abstract

This article presents the theoretical basis of the backcalculation method for determining the bearing capacity of the airport cement concrete pavement on the basis of the deflection data obtained in the field and the calculation results according to specialized software of the dynamic deflection equipment. Through experimental data of measuring actual deflection at taxiway S in Tan Son Nhat airport, compare the calculated bearing capacity according to the backcalculation theory and outputted value from the software has an error of 4% to 7%. It can be seen that, the backcalculation method of bearing capacity in cement concrete pavement according to the theory of multi-layer system structure gives similar results with the results calculated according to the specialized software of dynamic deflection equipment. The research results serve as the basis for evaluating the ability to use the existing dynamic deflection equipment in the world, for assessing the bearing capacity of the airport cement concrete pavement in the conditions of Vietnam.

Keywords: *Dynamic deflection; deflection basin; SHWD equipment; bearing capacity; PCN; cement concrete pavement; airport.*

1. Introduction

Cement concrete pavement is a commonly used structural solution for airport cover structures with features such as high durability, bigger bearing capacity, and long operating time, less sensitive to temperature conditions, meets the requirements of aircraft wheel load operations [1]. Before acceptance into use, or service of a new aircraft, the requirement to assess the bearing capacity of the pavement structure is mandatory. At the same time, the opration process, due to the influence of the impact factors of the aircraft load, climatic conditions, hydrothermal regime, the quality of the pavement has certain changes, so there is a need for periodically assessed according to ICAO regulations [2].

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For international airports, the annual assessment and publication of the pavement bearing capacity according to ICAO regulations is strictly required, with the following conditions: PCN ≥ ACN, where PCN is the pavement classification number (PCN = 2.P_{cp}, where P_{cp} is the allowable load capacity of the pavement) and ACN is the aircraft classification number [2, 3].

In the methods of assessing the airport pavement bearing capacity, the non-destructive testing method (NDT) with the use of dynamic deflection measurement equipment by falling weight (such as FWD - Falling Weight Deflectometer; HWD - Heavy Weight Deflectometer; SHWD - Super Heavy Weight Deflectometer), which is widely used with its advantages such as fast testing time, takes valuable spare time at some stages of the airport - aerodrome, and at the same time not cause damage to the pavement structure, bringing high reliability of the evaluation results [4-6]. Through the evaluation experiment, the obtained data will be the result of the pavement dynamic deflection corresponding to the experimental dynamic load of the equipment, the parameters of the pavement structure based on the design - operation records, through the backcalculation method, the parameters of the pavement structure layers will be obtained, thereby serving as a basis for calculating and assessing the bearing capacity of the airport concrete pavement [6]. Meanwhile, from the measured deflection data, use the specialized software that comes with the device to determine the pavement bearing capacity. With the equipment currently on the market being the exclusive product of the manufacturer, the software for calculating the bearing capacity has been encrypted with the copyright which is unknown about the basis of calculation.

Therefore, the article presents and clarifies the theoretical basis for calculating the bearing capacity from the measured deflection results of the airport cement concrete pavement in the field using a dynamic deflection measuring device, as a basis for applying the existing dynamic assessment equipment in the market, serving the evaluation of airport pavement bearing capacity in Vietnam conditions.

2. Theoretical basis for calculating the bearing capacity of cement concrete pavement according to the deflection data caused by the evaluation equipment in the field

Calculating the bearing capacity of the pavement from the deflection measurement data in the field caused by the falling weight device, also known as the backcalculation method [6, 7]. From the evaluated deflection measurement results, it is necessary to calculate the mechanical and physical parameters, which are typical for the material classes (elastic characteristics of concrete slab, foundation coefficient, elastic modulus and tensile and flexural strength of concrete slabs), thereby calculating the bearing capacity of the pavement.

2.1. Pavement deflection under the action of wheel load

Under the effect of wheel load, the part of the pavement that is bent which called the pavement deflection. When considering the concrete plate as isotropic, and uniform, the pavement deflection basin has a circular surface with the center as the center of the applied load (Figure 1).

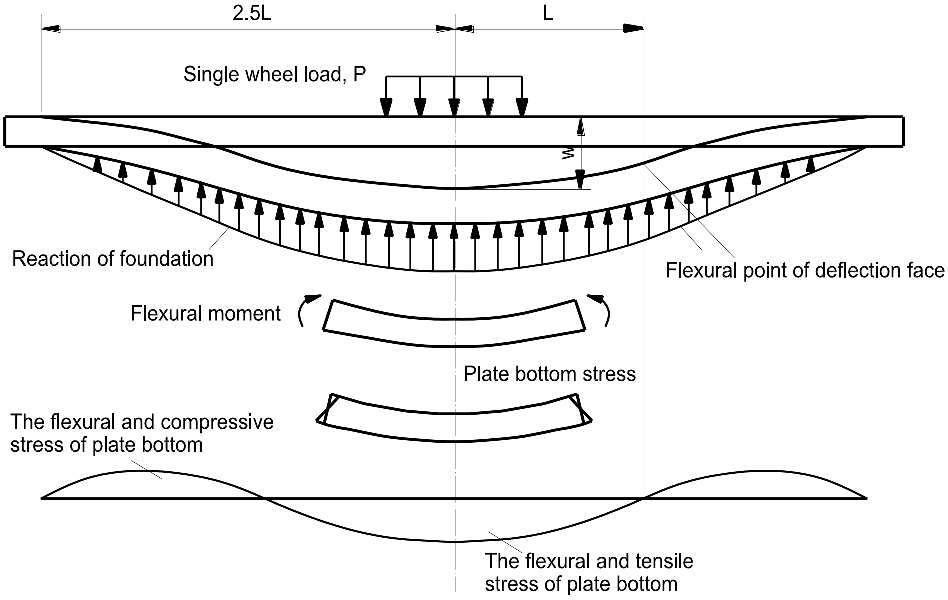

Figure 1. Deflection of cement concrete slab under the wheel load [8]

L is the elastic characteristic of the plate; w is the deflection under the load center.

According to the research and experimental results, the diameter of the deflection basin does not depend on the magnitude of the load but on the cylindrical flexural stiffness of the concrete slab (D) and the foundation coefficient (C): According to document [1-3], between the diameter of the deflection basin (D_{cv}) and the elastic characteristic of the slab (L), there is a relationship according to the formula:

$$D_{cv} = 5 \cdot L \tag{1}$$

When subjected to the affected load, the plate sags and transmits pressure to the subgrade (Figure 1). Exposing all forces acting on the plate in the z-direction, including applied load and ground reaction:

$$P = \int r(x, y) ds \tag{2}$$

where *P* is the affected load; *r*(*x*,*y*) is the ground reaction at coordinate (x,y), according to the one-base model: $r(x,y) = C \cdot w(x,y)$; $w(x,y)$ is the slab deflection at coordinate (x, y) which is assumed to be the foundation deflection; S is the area of the equal projection of the deflection basin.

Substituting the expression $r(x,y)$ into (2), we get: $P = \int_s C \cdot \mathrm{w}(x,y)ds = C \cdot \int_s \mathrm{w}(x,y)ds.$

On the other hand: $\int_s \mathrm{w}(x,y)ds = V.$

From that, the foundation coefficient will be:

$$C = \frac{P}{V} \quad (3)$$

V is the volume of the foundation deflection basin, taken as the volume of the pavement deflection basin, determined from experimental data, m^3.

When subjected to static loads, the foundation is considered an elastic material, so the foundation coefficient is called the static foundation coefficient; and when the applied load is the dynamic load, the foundation shows viscoelastic properties, so the foundation coefficient is called the dynamic foundation coefficient [8].

Thus, if we can determine the parameters of the deflection basin and the applied load, we can completely determine the elastic characteristic quantity of the cement concrete slab and the foundation coefficient. On that basis, it is possible to determine the remaining parameters such as the elastic modulus and the tensile and flexural strength of slab at the time of evaluation, thereby calculating the bearing capacity of the pavement at that time.

2.2. Determination of mechanical properties of pavement layers from measured deflection data

The backcalculation method to determine the bearing capacity of the cement concrete pavement at the time of evaluation needs data on the size and shape of the deflection basin caused by the test load, combined with the input data on the number of structural layers, the thickness of each layer according to the design profile.

In fact, there are three main methods used in backcalculation algorithms: Boussinesq solution, multilayer elastic theory method and finite element method [6].

On the basis of the theory of backcalculation, a series of equipment for assessing the bearing capacity of airport pavement with accompanying specialized calculation software have been born and used in the world such as: BISDEF of the US Army Corps of Engineers, BOUSDEF of Oregon State University, CHEVDEF, ISSEM4, ELMOD , LOADRATE, ELSEDEF, MODCOMP2, OAF, FWD AREA, SEARCH, WESDEF, VESYS, MODULUS 6.0, ELMOD 5.0, EVERCALC 5.0, BAKFAA, DAPS, etc. The calculation software accompanying the evaluation device is the copyrighted product of the manufacturer, in the form of a sealed box.

The following presents the calculation basis to determine the elastic characteristic parameters of the cement concrete slab, the foundation coefficient, the elastic modulus and the tensile and flexural strength of the slab by the method of multi-layer elastic system theory, the use some experimental coefficients for calculating of pavement bearing capacity.

a) Determining the elastic characteristics of pavement concrete slabs from field deflection measurements

To measure the deflection basin size of the pavement, the equipment usually has 3 to 9 measuring sensors, arrange the measuring sensors a certain distance from the center of the load. From the field test results, according to [6, 9-11], on the basis of the measured pavement deflection data, an experimental formula has been developed to determine the characteristic value of reinforced concrete slab as a basis for calculating the pavement bearing capacity. According to the FAA guidelines, they use the AREA method through empirical research in US conditions, determining the correlation between the shape of the deflection of the plate (through the degree of sag at some points on the deflection basin) with the slab stiffness, through the parameter of the concrete slab deformation resistance characteristic (the plate elastic characteristic). The AREA parameter is determined depending on the number of deflection measurement points and the location of the transducers on the pavement, which combines the effect of several measured deflections in the basin and is defined as follows [9-11]:

$$AREA = \frac{1}{2 \cdot w_0}\left[w_0 \cdot r_1 + \left(\sum_{i=1}^{n-1} w_i \cdot \left(r_{i+1} - r_{i-1} \right) \right) + w_n \left(r_n - r_{n-1} \right) \right], \text{ (inch)} \tag{4}$$

where w_0 is the deflection at center of load, inch; r_1 is the distance between the center of the load plate and the first sensor, inch; w_i is the measured deflection (i = 1, n), inch; n is the number of deflector sensors minus one; r_i is the distance between the center of the load plate and sensor i^{th}, inch.

From the results of calculating the parameter AREA, the dynamic elastic characteristic of the concrete slab is determined by the formula [7, 9, 12]:

$$L_d = \left[\frac{\ln\left(\frac{A - AREA}{B} \right)}{C} \right]^D, \text{(inch)} \tag{5}$$

where A, B, C and D are experimental constants, depending on the number of sensors and the distance of sensors, according to US conditions. When the assessment equipment has 9 sensors, of which 7 are 0, 12, 24, 36, 48, 60 and 72 inches from the center of the load, respectively, the constants A, B, C, D are taken according to Table 1.

Table 1. Constants based on the AREA method [7, 9]

The AREA method	**Constant**			
	A	**B**	**C**	**D**
The device has nine sensors	72	242.385	-0.442	2.205

b) Determining the foundation coefficient from field measured deflection results

When the elastic characteristic of the concrete slab is known, the dynamic foundation coefficient is determined by the formula [8, 13]:

$$C_d = \frac{P_{td}}{8 \cdot w_0 \cdot L_d^2} \left\{ 1 + \frac{1}{2\pi} \cdot \left[\ln\left(\frac{R}{2 \cdot L_d} \right) - 0.673 \right] \cdot \left(\frac{R}{L_d} \right)^2 \right\}, \ (\text{N/m}^3) \tag{6}$$

where C_d is the dynamic foundation coefficient, N/m^3; L_d is the dynamic elastic characteristic of the concrete slab, m; R is the converted wheel track radius, m, taken as the value of the plate radius to the pavement of the dynamic loading device; P_{td} is the applied load of the falling weight device acting on the press plate, N.

When the applied load is dynamic load, the calculated foundation coefficient is the dynamic foundation coefficient.

c) Determining the elastic modulus of the pavement concrete slab

When the elastic characteristic of the concrete slab and the foundation coefficient are known, the elastic modulus of the concrete slab is determined by the formula [8]:

$$E = \frac{12 \cdot C_d \cdot L_d^4 \cdot (1-\mu^2)}{h^3}, \ (\text{N/m}^2) \tag{7}$$

where E is the elastic modulus of concrete, N/m^2; h is the thickness of concrete slabs at the evaluation site, m; μ is the Poisson's coefficient of concrete.

d) Determining the tensile and flexural strength of the pavement concrete slab

When the elastic modulus has been determined, the tensile and flexural strength of concrete is calculated according to the formula of American Concrete Institute [1, 8]:

$$R_{ku} = \frac{43.5 \cdot E}{10^6} + 488.5, \ (\text{Psi}) \tag{8}$$

where E, R_{ku} are expressed in Psi.

Because concrete is an elastic material, the elastic modulus and the tensile and flexural strength parameters of the concrete obtained from the static and dynamic tests are the same [8].

e) Determining the pavement bearing capacity at the time of assessment

When the parameters of the concrete layer thickness, the elastic modulus, the tensile and flexural strength of concrete slab, and the foundation coefficient are known, the allowable load is determined according to the formula [8, 13]:

$$P_{cp} = \frac{R_{ku} \cdot h^2}{0.275 \cdot (1+\mu) \cdot \left[\log\left(\frac{E \cdot h^3}{C \cdot R^4} \right) \right]}, \text{ (N).} \quad (9)$$

where P_{cp} is the allowable static bearing capacity, then the unit is converted to tone (T); C is the static foundation coefficient, N/m^3, is taken as a half of the dynamic foundation coefficient according to [2, 3, 8]. Other parameters as mentioned above.

3. Calculation and determination of concrete pavement bearing capacity by SHWD device in the field

3.1. Method of measuring dynamic deflection by SHWD device

a) Introduction to SHWD device

Currently, in Vietnam, some airports have been using SHWD equipment, which manufactured by Pavetesting in the UK in 2018.

- The main parts of the SHWD device (Figure 2):

+ Impulse generator, including load block and shock absorber;

+ Circular press plate with diameter D is 30 cm, made of alloy, the bottom has a thin rubber layer, and the center of the plate has a hole to place the sensors;

+ The deflection probes: Nine probes are installed in a straight line on support along the measuring vehicle direction. There is one probe placed at the center of the press plate, and the other probes are at a distance from the center, as shown in Table 2. In actual conditions, it is possible to change the position and upgrade the number of deflection probes.

Table 2. Distance between measuring heads relative to the center of the press plate [14]

D01 (center of the press plate)	D02 (mm)	D03 (mm)	D04 (mm)	D05 (mm)	D06 (mm)	D07 (mm)	D08 (mm)	D09 (mm)
0	300	600	800	1100	1400	1700	1900	2100

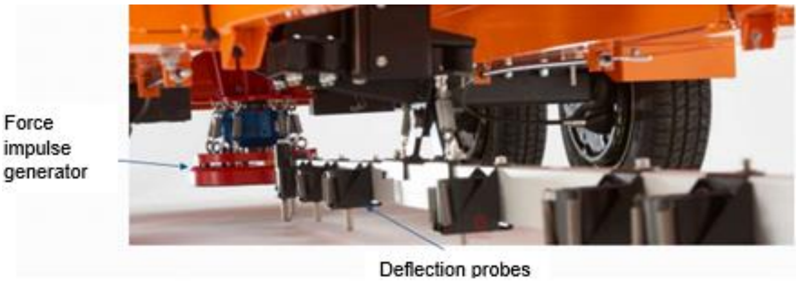

Figure 2. Main components of the SHWD device [14].

b) Experiment sequence

- Collect deflection data: Install the SHWD device into the trailer, and re-align the distance of the measuring heads. Using a tow truck to reach the location to be assessed, the load is applied to obtain the dynamic deflection values. According to [12], the surface temperature of concrete slab at the time of evaluation is regulated not to exceed 38ºC, in order to limit the expansion and warping of the panels affecting the accuracy of pavement deflection measurements.

- From the dynamic deflection data by the DAPS backcalculation software that comes with the device, we get the datasets to enter into the COMFAA software by using the COMFAA support 3.0 file.

- Export PCN value at each deflection measurement point on the pavement by COMFAA software.

3.2. Measuring dynamic deflection by SHWD equipment in the field

The test to measure the dynamic deflection of the cement concrete pavement on taxiway S in Tan Son Nhat airport in Vietnam, at position 2.86 m from the center of the taxiway (Figure 3), was performed using SHWD 350 kN device [14].

The location of the measuring probes of the device is shown in Table 2.

According to design data, the structure of taxiway S includes the following layers:

- Steel mesh reinforced concrete, grade 350/45, average thickness 0.39 m.
- Cement concrete, grade 150/25, average thickness 0.38 m.
- Graded aggregate base, average thickness 0.18 m.
- Sand, average thickness 0.50 m.
- The natural subgrade is sandy clay soil.

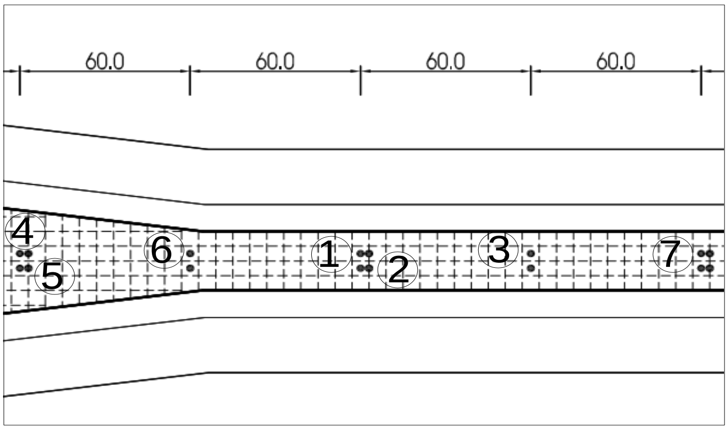

Figure 3. Dynamic deflection measurement at some locations on taxiway S at Tan Son Nhat airport by SHWD [14].

Table 3 shows the results of dynamic deflection and effective load of 7 measuring points at taxiway S at Tan Son Nhat airport, determined at the time when the assessed load at each measurement point is the maximum.

Table 3. Measured dynamic deflection results of 7 measuring points on taxiway S [14]

Experimental parameters	**Measuring point**						
	1	2	3	4	5	6	7
Experimental load (kN)	239.46	246.91	248.17	254.66	249.92	250.42	250.92
Deflection at D1 (μm)	195.00	215.64	204.89	178.83	185.08	186.55	213.4
Deflection at D2 (μm)	155.83	174.13	163.24	143.4	154.22	149.23	184.19
Deflection at D3 (μm)	138.73	161.13	147.26	128.53	138.68	134.03	167.45
Deflection at D4 (μm)	132.86	153.87	137.36	120.64	133.08	127.69	158.17
Deflection at D5 (μm)	118.78	139.45	124.11	106.86	118.24	116.94	141.97
Deflection at D6 (μm)	101.91	123.73	104.84	94.48	101.24	99.99	124.22
Deflection at D7 (μm)	84.51	105.96	90.55	78.27	88.59	89.02	106.62
Deflection at D8 (μm)	81.64	97.26	85.82	73.46	84.1	83.62	98.37
Deflection at D9 (μm)	74.18	86.96	77.78	66.29	75.24	77.24	88.85

From dynamic deflection data, use DAPS specialized software according to the device [14] to create a dataset that is input into COMFAA software and output PCN results as shown in Table 4.

Table 4. PCN results after calculation using COMFAA software [14]

Measuring point	**Experimental load (kN)**	**PCN value**
1	239.46	92
2	246.91	91
3	248.17	91
4	254.66	93
5	249.92	94
6	250.42	93
7	250.92	93

3.3. Calculation of pavement bearing capacity by backcalculation method

From the measured deflection results and the experimental load as shown in Table 3, using the backcalculation method presented in Section 2 above, the calculation results of the pavement bearing capacity are obtained. Applying formulas (4) ÷ (9), calculate the values of the quantities AREA, L_d, C_d, E, R_{ku}, P_{cp} of the evaluated pavement as in Table 5.

Table 5. Calculation result of bearing capacity value

Measuring point	**AREA (inch)**	**Elastic characteristic L_d (inch)**	**Foundation coefficient C_d (MN/m^3)**	**Elastic modulus E (MPa)**	**Tensile and flexural strength R_{ku} (MPa)**	**Permissible load P_{cp} (T)**	**Value PCN_{tt}**
1	48.53	39.26	153	29825.32	4.64	478.7	96
2	51.05	43.58	116	34330.21	4.83	479.9	96
3	48.41	39.06	152	29115.84	4.61	476.5	95
4	48.55	39.28	177	34634.61	4.84	499.8	100
5	50.92	43.35	138	40060.18	5.08	50.51	101
6	49.54	40.90	154	35410.83	4.88	49.58	99
7	52.82	47.12	102	41275.20	5.13	49.54	99

From Tables 4 and 5, we have the results of comparing the PCN value (characteristic of the bearing capacity of the pavement) between the calculation by theoretical formula and the value from the specialized software accompanying the dynamic deflection equipment as in Table 6.

Table 6. PCN value comparison by theoretical formula and specialized software

Measuring point	**Theoretical calculated value PCN_{tt}**	**The output value from software PCN**	**Error (%)**
1	96	92	3.92%
2	96	91	5.19%
3	95	91	4.52%
4	100	93	6.96%
5	101	94	6.95%
6	99	93	6.20%
7	99	93	6.14%

Comment: From the actual assessment of the cement concrete pavement of the taxiway S at Tan Son Nhat airport, the SHWD device has measured the dynamic deflection, and through the supporting software, the PCN values have been output to quickly and conveniently assess the airport pavement bearing capacity. Through comparing the calculated value by the backcalculation method with the value output from the software with errors as shown in Table 6, it is found that the software calculates accompanying the device compared with the calculation theory presented by the authors with errors which is acceptable. In the article, both calculation methods use the dynamic foundation coefficient relationship equal to twice the static foundation coefficient according to the data recommended by the United States (US) [2, 3]. Although the results of the calculation of the bearing capacity according to the above two methods have similar results, the error is within the range of about 4% to 7%, but the calculation results are still based on the formulas using the coefficients experiment in the conditions of the US, in order to apply effectively and ensure high accuracy in the conditions of Vietnam, additional studies are needed to clarify the influence of climate conditions, materials, in which the static foundation coefficient parameter is taken as 1/2 of the dynamic foundation coefficient, the degree of dependence of the static foundation coefficient on the dynamic foundation coefficient depends on the geological and hydrological conditions of Vietnamese soil.

4. Conclusion

The article presents the results of the comparative evaluation of two methods of calculating the pavement bearing capacity of Tan Son Nhat airport from the software accompanying the SHWD device and the results of backcalculation of the pavement bearing capacity from the measured deflection data in the field. From the analysis and clarification of the calculation basis, a way to determine the PCN pavement classification value according to ICAO regulations is given. Since then, when the field deflection data is available, the static calculation method is an approach to assess the airport concrete pavement bearing capacity without the need for specialized software accompanying the device.

Through analytical formulas, engineers can make calculation programs, making the work of calculating the pavement bearing capacity faster and more convenient.

Through calculation according to methods with measured data at taxiway S, Tan Son Nhat airport, it was found that the results have an acceptable level of agreement, the difference between the two methods of seven measuring points is of 4% to 7%. However, in order to study the suitability of the pavement bearing capacity assessment devices by dynamic deflection measuring devices in Vietnamese conditions (the experimental coefficients in the accompanying calculation software of the device), it is necessary to conduct more field trials under Vietnamese conditions.

The application of this device has made it possible to assess the pavement bearing capacity quickly and conveniently. Thus, the authors continue to recommend the application of dynamic deflection measurement equipment more widely at airport constructions in Vietnam, not only assessing the pavement bearing capacity for inspection and acceptance upon completion of construction but also evaluating the bearing capacity during the operation of the airport to determine the remaining bearing capacity in order to predict the service life to have the best solutions for the maintenance, repair or upgrading work.

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PHÂN TÍCH CƠ SỞ LÝ THUYẾT ĐÁNH GIÁ SỨC CHỊU TẢI MẶT ĐƯỜNG BÊ TÔNG XI MĂNG SÂN BAY Ở VIỆT NAM BẰNG THIẾT BỊ ĐO ĐỘ VÕNG ĐỘNG

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Tóm tắt: *Bài báo trình bày cơ sở lý thuyết phương pháp tính ngược, xác định sức chịu tải mặt đường bê tông xi măng sân bay trên cơ sở số liệu độ võng đo được tại hiện trường và kết quả tính toán theo các phần mềm chuyên dụng của thiết bị đo độ võng. Qua số liệu thực nghiệm đo độ võng thực tế tại đường lăn S sân bay Tân Sơn Nhất, so sánh sức chịu tải tính toán theo lý thuyết tính ngược và giá trị xuất ra từ phần mềm có sai số từ 4% đến 7%. Có thể thấy rằng, phương pháp tính ngược sức chịu tải của mặt đường bê tông xi măng theo lý thuyết kết cấu hệ nhiều lớp cho kết quả tương tự với kết quả tính theo các phần mềm chuyên dụng của thiết bị đo. Kết quả nghiên cứu làm cơ sở cho việc đánh giá khả năng sử dụng thiết bị đo độ võng động hiện có trên thế giới, cho việc đánh giá sức chịu tải mặt đường bê tông xi măng sân bay trong điều kiện Việt Nam.*

Từ khóa: Độ võng động; chậu võng; thiết bị SHWD; sức chịu tải; PCN; mặt đường bê tông xi măng; sân bay.

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