■ 論　文 ■

INVESTIGATION OF SUBSURFACE CAVITIES UNDER PAVEMENT STRUCTURES WITH DYNAMIC CONE PENETROMETER TESTS

동적관입시험(DCP TESTS)에 의한 포장체 하부구조내 공동(空洞)현상에 관한 조사

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목　차

요　약

이 논문은 포장체 하부구조내 공동(空洞)현상에 대한 위치를 규명하는데 있어서 신속하면서, 간단하고 신뢰성있는 방법을 제시하고자 한다. 동적관입시험(DCP)을 사용하여 콘크리트 슬라브하부의 노상토에 대한 강도를 측정하였다. 타격회수에 대한 침하의 양으로 측정되는 동적관입침하율을 비교하여 포장체하부의 연약지반에 대한 위치를 규명하였다. 콘크리트 포장체 하부의 공동(空洞)현상 및 연약화된 노상토에 대한 정보를 얻고자 하는 엔지니어를 위하여 시험방법 및 결과분석 등을 현장시험을 통하여 체계적으로 설명하였다.

I. INTRODUCTION

Subsurface cavities under pavements and buildings are caused by various factors, including deteriorated or damaged buried pipes and the internal erosion of subsurface soils. Internal erosion is a slow process by which the subsoil structure unravels due to the migration of soil particles, mostly transported by groundwater or water from leaking pipelines to adjacent or underlying soil strata[1]. In an advanced stage, this will cause cavities in the subgrade material resulting in subsidence of the ground, leading to the cracking and sinking of pavements and buildings. If subsurface cavities are not detected and repaired, the structures and pavements could collapse, causing severe accidents and significant damage to property. Therefore, early detection and monitoring of subsurface cavities is important.

Various techniques have been used for assessing the strength and structural condition of subsurface soils. Most of these techniques are suitable for locating and evaluating subsurface cavities. One of the traditional methods is the penetrometer. Recent developments include the use of vehicle-mounted ground penetrating radar (GPR), which was first developed in 1990[2]. The GPR technique is effective for the location and evaluation of voids and subsurface cavities; however, the GPR equipment can be expensive and requires significant experience to operate. In addition, highly skilled personnel are required to interpret the data.

The dynamic cone penetrometer (DCP) has been used widely around the world to determine the strength of pavement foundations since the 1970[3,4]. However, the application of DCP for evaluating surface cavities under the pavement structures is limited. This paper presents the application of the DCP test for detecting voids, cavities, and areas of general weakness under a Portland cement concrete (PCC) slab and explains the method for interpreting the DCP test data. The technique has been found to be simple, quick, reliable and inexpensive. Also, recommendations are presented how the DCP technique can be used effectively to identify the location of subsurface cavities on roadways and buildings.

II. DYNAMIC CONE PENETROMETER TESTS

The DCP is a simple handhold device for measuring the in-situ strength of paving materials and subgrade soils (Figure 1). Although the DCP has been available since the 1970s, very few agencies are familiar with its potential in the investigation of pavement material strength. It consists of a handle, which is used to hold the DCP plumb and limit the upward travel of the hammer, a 8 kg (17.7 lb) hammer, which is raised and dropped to transfer its energy to the rod; a steel rod with a diameter of 16 mm (0.65 in); and a cone with a 30° or 60° angled point[3]. The cone is driven into the soil by raising and dropping the hammer.

A simple description of a DCP test procedure is that the cone is driven into the pavement/subgrade by raising and dropping the hammer. The cone penetration is recorded for each drop and is called the penetration rate (PR). The cone is typically driven 0.9 to 1.2 m (36 to 48 in) at each test location. The typical DCP test takes 5 to 10 minutes, but when the surface layer needs to be cored the test can take up to 30 minutes.

The DCP penetration rate (PR), mm/blow (in/blow), has been used to identify the pavement layer boundaries and soil strata. The U.S. Army Corps of Engineers[4] recommends that the PR should be recorded after 10 blows for $2.5 \text{ mm} \leq PR \leq 12.5 \text{ mm}$ ($0.1 \text{ in} \leq PR \leq 0.5 \text{ in}$). If $PR > 25$ mm (1 in) it should be recorded for each blow. A detailed description of the DCP testing procedure can be found in the literature[4].

A typical correlation between the penetration rate (PR) and the California Bearing Ratio (CBR) value can be expressed:

$$CBR = \frac{405.3}{PR^{1.259}} \tag{1}$$

$$Log\, CBR = 2.20 - 0.71\,(Log\, \mathrm{PR})^{1.5} \tag{2}$$

here PR is in mm/blow. Equation 1 is for a cone with a

60° angled point[5] and Eq. (2) is for a cone with a 30° angled point[6]. It is interesting to note that the CBR values from Eqs. (1) and (2) are almost identical when PR is greater than 3. It implies that the cone angle affects small to the PR value.

DCP penetration rates and their corresponding CBR values for some typical base and subgrade materials are given in Table 1. In general, good granular base course materials exhibit CBR values in excess of 80. Granular subbase materials generally have CBR values of between 20 and 80[7]. Fine grained subgrade materials have typical CBR values of 5 to 15[8], which translates to a penetration rate of 14 to 35 mm/blow (0.5 to 1.4 in/blow).

In interpreting DCP data, one may divide the soil material under investigation into very thin layers. Because the strength of the material can be determined for every blow, the DCP is able to determine immediately when there is a change in the strength of the material. This is very useful in determining exact locations of weakness and cavities. Very little difficulty is experienced with the penetration of normal pavement layers or lightly treated material. It is, however, more difficult to penetrate layers treated with a high percent of asphalt or Portland cement. Treated materials can yield a penetration rate on the order of 0.3 to 1.0 mm/blow (0.01 to 0.04 in/blow).

If there is no penetration after 20 consecutive blows, it is assumed that the DCP cannot penetrate the material at the test location[3]. It has to be determined if the DCP has encountered an obstruction or is in a zone of very stiff material. A hole can be drilled through the obstruction to determine if it is a boulder or a stiff layer. Alternatively, the DCP can be relocated and a new test carried out close to the original hole in order to avoid the obstruction or to confirm the presence of a stiff layer. The DCP gives acceptable readings when used in coarse materials unless the cone bears directly on a stone. Acceptable readings have been obtained in gravels containing a random distribution of single size stones up to a diameter of 75 mm (3 in). The DCP can normally be driven through both single and double seal surface treatments but not through asphalt concrete and Portland cement concrete[3].

III. SITE INVESTIGATION

During routine repairs and rehabilitation, significant erosion of the soil located around an abandoned sanitary waste line was noted beneath PCC slabs in a large industrial complex in Champaign, Illinois. The abandoned pipeline is a 200-mm (8.0-in) diameter cast iron pipe and is located approximately 2.44 m (8 ft) beneath the concrete floor slab of the facility. A schematic diagram of the factory floor, the abandoned pipeline, and the test locations are illustrated in Figure 2.

It appeared that before being abandoned, the cast iron pipe had deteriorated to the extent that effluent had leaked from the pipe and eroded the surrounding soil. This may have occurred at several points along the path of the pipeline. To strengthen the subgrade soil and eliminate the cavities at the location discovered during maintenance, the eroded area was filled with controlled low-strength concrete material (flowable fill). It was decided that close monitoring and subsurface exploration should be performed to determine how widespread this problem was and to suggest remedial measures. The handhold slab coring equipment and a DCP were selected for the investigation because the abandoned pipeline is located in an area of the factory that had limited access and space for other kinds of equipment, and there was the need for quick and cost-effective results. The factory floor was a 150 mm (6.0 in) thick concrete slab underlain with 100 mm (4 in) coarse sand and a clayey sand fill material over 3 m (10 ft) thick overlying the natural subgrade.

The site investigation for this project consisted of site reconnaissance, coring of the PCC concrete slab (because the DCP cannot penetrate PCC concrete), and DCP testing that followed the guidelines of the Corps of Engineers[4]. The path of the abandoned sanitary waste line was surveyed to determine the most appropriate areas to be cored and tested. The selection of the areas was based on accessibility and the ability to test in those areas without much interruption of work at the factory. The PCC floor slab was cored at four locations offset approximately 450 mm (18 in) from the abandoned pipeline. At each core location, a DCP was extended into the underlying subgrade, to a depth of approximately 2.5 m (8 ft).

Coring work was performed using water-cooled diamond bit equipment. The cores, approximately 100 mm (4 in) in diameter were extended through the factory floor slab. The coring process was just to expose the soil under the concrete slab for DCP testing to begin.

Immediately after the coring work was completed, the underlying soils were tested at each core location using the DCP (illustrated in Figure 1). The 60° cone was used in this investigation. Upon completion of the coring and DCP work, the core holes were patched with a cement patching material. Core locations identified as having potential erosion areas were filled with sand and capped with a thin layer of low-strength PCC for easy future access.

IV. DATA ANALYSIS

The results of the DCP testing are presented in Figures 3 through 6. At core location A, the DCP penetration rate was consistent, ranging from 6.4 to 31.8 mm/blow (0.25 to 1.25 in/blow). This corresponds to a CBR value of 5.2 to 39.5. Clayey sand fill materials from past research have typical CBR values ranging from 5 to 15[8]. This is consistent with the estimated range of CBR for the fill material.

From the penetration rates plotted in Figure 3, four zones with varying penetration rates (CBR values) can be identified (Table 2). The CBR values are calculated using Eq. (1). In general, no extremely weak areas or areas of potential erosion or settlement were identified at location A. Zone 1 always showed some relative weakness. It is believed that water from the coring operation inundated and softened the upper layer of the subgrade soil.

The DCP penetration rate at core location B varied significantly, from 3.8 to 115 mm/blow (0.15 to 4.5 in/blow, Figure 4). This corresponded to a CBR value ranging from 1 to 75 percent. DCP penetration rates greater than 35 mm/blow (1.4 in/blow), which is equivalent to a CBR value less than 5, indicate areas of extreme weakness and potential erosion or cavities. The soil profile can again be grouped into four zones with varying penetration rates (CBR values), as shown in Table 2.

At location C, the penetration rate ranged from 6.4 to 70 mm/blow (0.25 to 2.8 in/blow, Figure 5). The top 0.3 m (1 ft) showed unexpected weakness. The high penetration rate in this area was attributed to the loss in strength of the clayey sand fill material, which was inundated by water from the coring operation and not necessarily due to the presence of eroded soil or cavities. This is similar to what was observed for location A. Dividing the soil profile into zones of different penetration rates (CBR values) once again identifies four clear zones, with CBR values ranging from 2 to 40 (Table 2).

The DCP penetration rate at core location D was the most consistent, ranging from 6.4 to 23 mm/blow (0.25 to 0.9 in, Figure 6). The corresponding CBR values range from 8 to 40. The penetration rate and CBR values across the path of the DCP for location D are given in Table 2. The DCP testing was terminated at a depth of 1.8 m (70 in) because a stiff layer was encountered. The stiff layer is suspected to be low-strength concrete material that was used to fill cavities located along an adjacent section of the pipeline.

The penetration rate of the coned tip of the DCP for a fixed amount of applied energy gives an indication of the resistance of the soil to penetration and hence its strength. The strength of subsurface materials tend to vary gradually within a given material thickness. A sudden loss in strength can therefore be attributed to an area of weakness. The area of weakness may be due to any or a combination of the following reasons:

- Poor compaction of the material layer; that is, if the material is not part of the natural subgrade but was placed as part of the pavement or building foundation.
- A saturated region of soil.
- Erosion of the material.
- Settlement of soil located over an eroded zone or cavity.

In this study, the concrete slab was laid on 100 mm (4 in) of sand placed on fill material which consisted of clayey sand. Because the problem of erosion and potential cavities was localized around the corroded drainage pipeline, it is reasonable to suggest that the occurrence of weak areas and potential cavities is not due to poor compaction during the filling operation.

V. LIMITATIONS TO DCP TESTS AND ANALYSIS

The DCP test, though quick and simple, has some limitations. These limitations can be overcome as engineers become more experienced with the use of the DCP. Some of the limitations are as follows:

- Should the cone of the DCP equipment hit a large stone, boulder, or even the foundation concrete of a building, further penetration may be small or nonexistent. This can be interpreted as a very stiff layer or bedrock.
- It is not possible to determine the soil type at a given depth of penetration of the DCP cone and rod. This implies that the engineer will have to depend on past investigations or designs to know the type of material being dealt with, or will have to core and auger to obtain soil samples.
- The friction between the DCP rod and surrounding soil increases with depth. This is especially true for cohesive soil and may result in an overestimation of the strength of the soil material.
- It may not be possible to determine the in-situ moisture content of the soil material. Because the strength of a material is directly related to its moisture content, this may result in over- or underestimating subgrade material strength.

VI. SUMMARY AND CONCLUSION

The problem of subsurface cavities occurs commonly in areas with subsurface drainage. This is especially true for drains and culverts under roadway pavements. With good planning, the DCP technique outlined can also be used to investigate subsurface cavity problems under pavement structures. Efficient identification and monitoring of cavities can reduce the number of accidents and damage caused by soil erosion around dams and culverts. The DCP testing techniques do not require much manpower or skill. The testing is also relatively inexpensive.

On roadways, the most likely place to find subsurface cavities is around pipes in the right-of-way, typically at roadway intersections. These are identified at the surface by the occurrence of depressions. The areas to be investigated should be divided into appropriately sized square grids. DCP testing should be conducted at all four corners of the square sections mapped out on the grid. The results from the DCP testing should be plotted for the various sections of the testing grid. This plot, preferably three dimensional, will identify the area in plan and section of weakness when compared to the typical strength of the material. The volume of the affected area can also be estimated.

In this study, the DCP was used in the nondestructive evaluation of subsurface materials. (The test method is considered nondestructive despite the core extrusion.) The DCP was sufficiently sensitive to highlight the difference in strength of the subgrade material at different depths. The paper presented the basic DCP test and correlations of DCP penetration rate to the CBR strength of the soil material from previous studies. The paper described in detail methods for interpreting DCP results and analyzing to detect subsurface cavities and areas of weakness in the subgrade. The dynamic cone penetrometer is also a very useful tool for pavement evaluation and construction inspection. As more engineers begin using the DCP, methods of interpreting test data will become more refined and standardized, making it a more valuable tool in pavement and geotechnical engineering.

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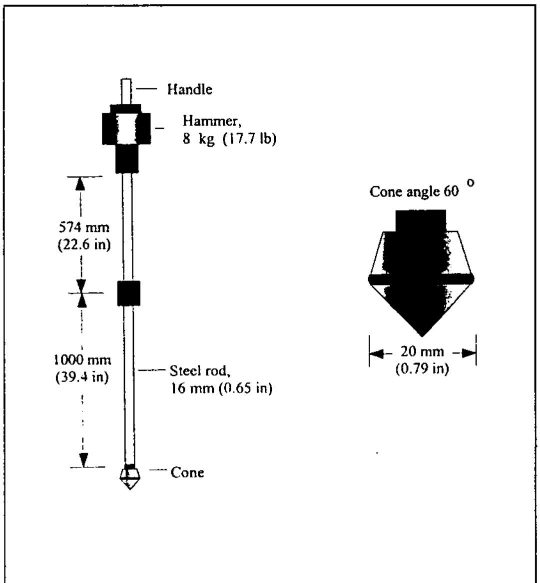
〈Table 1〉 Typical Penetration Rate and *CBR* Values for Soils.

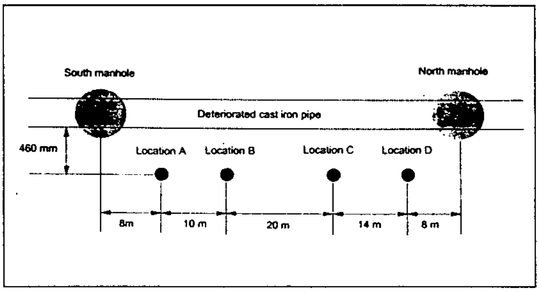
Soil Type	Typical Field *CBR* value	Typical Penetration Rate, mm/blow
Gravel	25 - 50	5 - 9
Sand	10 - 20	10 - 17
Clay	5 - 15	12 - 30



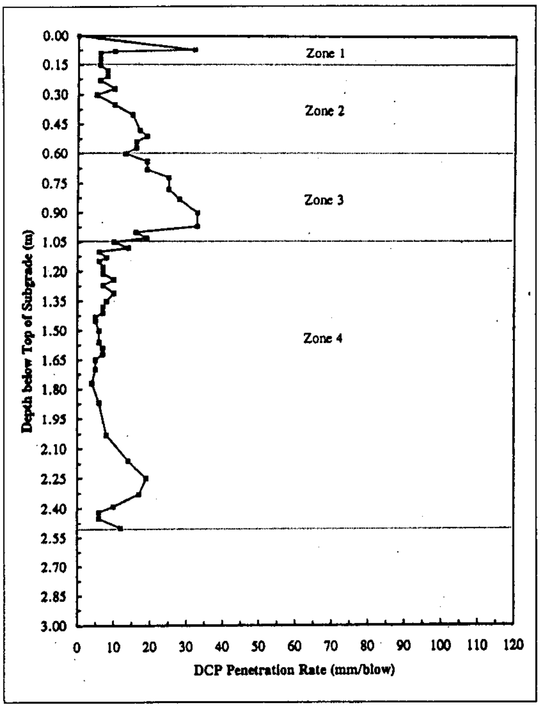
〈Figure 1〉 Illustration of dynamic cone penetrometer

〈Table 2〉 Locations with Corresponding Penetration Rate and *CBR* Values.

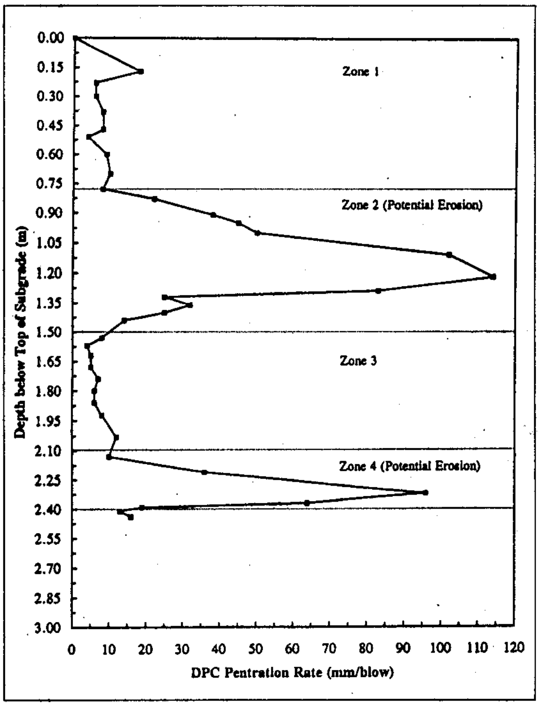
Location of DCP	Zone	Depth (m)	Avg. *PR* (mm/blow)	Avg. *CBR*	Potential erosion or settlement
A	1	0.0 - 0.15	15	13.4	No
	2	0.15 - 0.6	8	30.0	No
	3	0.6 - 1.05	23	8.0	No
	4	1.05 - 2.5	7	35.0	No
B	1	0.0 - 0.80	7.5	33.0	No
	2	0.80 - 1.5	60	2.3	Yes
	3	1.5 - 2.1	7	35.0	No
	4	2.1 - 2.4	52	2.7	Yes
C	1	0.0 - 0.3	40	3.9	No
	2	0.3 - 0.9	25	7.0	No
	3	0.9 - 1.4	38	4.1	Yes
	4	1.4 - 2.5	10	22.2	No
D	1	0.0 - 0.3	12	17.6	No
	4	0.3 - 1.8	5	53.2	No



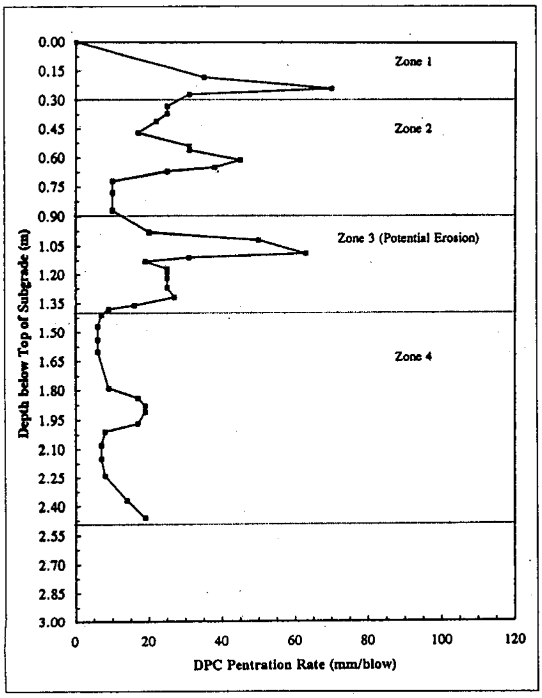
〈Figure 2〉 Schematic diagram of factory floor, abandoned Pipeline and test locations.



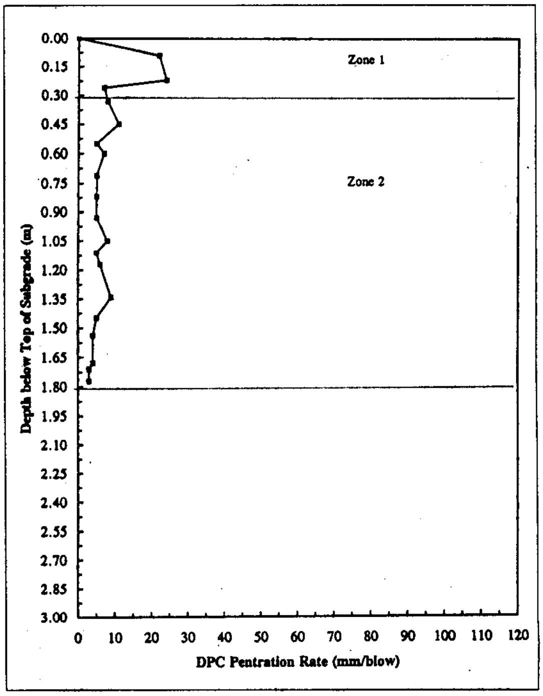
〈Figure 3〉 DCP penetration profile for test location A.



〈Figure 4〉 DCP penetration profile for test location B.



〈Figure 5〉 DCP penetration profile for test location C.



〈Figure 6〉 DCP penetration profile for test location D.