Nature and Detection of Void-Induced Pavement Failures

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Pavement failures caused by substructure cavities, or voids, have recently become a widespread problem in Japanese roads. Several cities in Japan have reported these problems. To ensure the safe flow of traffic and to avoid pavement failure-induced traffic accidents, the detection of sinkholes became a top priority. Acting on this situation, the Ministry of Construction developed a sinkhole detection vehicle that makes it possible to detect subsurface cavities with higher speed and precision. The Ministry of Construction formed a coordinating agency to oversee the implementation of this technology. This agency made actual site surveys and analyzed the results to ascertain the mechanical properties of subsurface cavities. With this knowledge, in 1992 an effective sinkhole detection method was developed. The method utilizes ground penetrating radar and a bore hole camera as field data acquisition tools. The detection method relies on using the analysis tools to provide an increasingly detailed look at the pavement substructure: from a general survey to a specific survey. Through many void identifications during daily operations in the field, we have arrived at an understanding of the nature of subsurface voids. This understanding has allowed pavement maintenance and construction engineers to catch voids before they evolve to dangerous pavement failures.

A growing number of accidents have been reported in recent years on the highways and roads of Japan that have been caused by sinkholes. As a result of this situation, it became necessary to develop a way to detect sinkholes that was quick, accurate, reliable, and nondestructive to the pavement. The Ministry of Construction accepted this challenge and in 1990 developed the first practical sinkhole detection method in the world. The method relies on a primary survey with vehicle-mounted, low-frequency ground penetrating radar (GPR), a secondary survey using hand-operated GPR, and a final confirmation with a bore hole camera (BHC).

DEVELOPMENT OF A SINKHOLE DETECTION VEHICLE

Previous sinkhole detection surveys were performed using portable GPR devices or infrared devices. From a careful study of the results of these surveys, it was determined that these methods were not satisfactory because they were not accurate enough and the speed of the survey was too slow. Therefore, before development, the Ministry of Construction constructed a test field in which sample voids, pipes, and other subsurface anomalies were buried. Various methods of detection (not immediately relevant to this discussion) were used in this controlled environment to determine which method was the most effective at subsurface detection. The public dissatisfaction over the many sinkholes in Japan caused this situation to be pursued on an emergency basis. The analysis tools were mounted in a convenient vehicle as shown in Figure 1.

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FEATURES OF THE SINKHOLE DETECTION VEHICLE

Penetration Depth

The low frequency penetrates to approximately 1.2 to 1.5 m. This figure will vary based on the electromagnetic conductivity of the soil composition. This target depth specification was chosen based on investigation of the records of the depths of actual sinkholes. The evolution of a sinkhole is shown in Figure 2; loose sands migrate upward from their point of origin (see also Figure 10) to the pavement subsurface.

Width of Inspection

The inspection path covered during one pass is greater than 2 m. The GPR antennas have a field width of 1 m each and two antennas were installed in a parallel mounting configuration on the vehicle. Using this method, it became possible to inspect almost all of a lane on a single pass with minimum obstruction to normal vehicular traffic. The mounting style and position of the antennas is shown in Figure 3.

Speed of Inspection

The vehicle can perform the survey function at over 20 km/hr. The previously used GPR inspection methods cannot proceed at over 2 to 4 km/hr, but the developed vehicle has a hydraulic lifter, which makes possible running and turning the GPR antenna without repeated antenna to ground contact. One data acquisition period is now over 10 times faster than previously used GPR methods, and it is possible to survey at over 20 km/hr.

It should be noted that the problem of dispersed radio frequency isolation was addressed by the installation of electromagnetic wave damping skirts around the perimeter of the antennas to form a barrier between the antenna, the pavement surface, and the damping skirt.

FIGURE 1 Sinkhole detection vehicle.

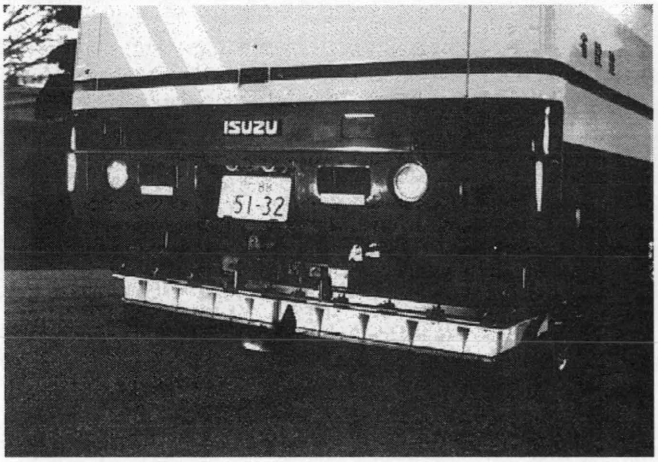


FIGURE 3 Mounting of the dual antennas at the rear of the vehicle.

Void Detection Capability

In the previously mentioned field work, 212 possible voids were identified with the method and 191 voids were confirmed by cutting and filling. This produces a nominal success rate of about 91%. The overriding concern with this void detection method is to avoid costly cut-and-fill operations. The importance of this method becomes apparent in the secondary survey when the marginal void targets can be determined to be void or nonvoid areas. The system can distinguish voids from other buried objects. This process was proven in test fields, and also in actual site surveys in which noise problems caused by poorly matched circuit components and tip deflection were finally eliminated, suitable frequencies of GPR wave were chosen, and the typical signal pattern of the void was determined. Video cameras are mounted at the front and left and right of the vehicle as shown in Figure 4. Their recorded data are synchronized with the GPR data to provide distance measurement. This technique ensures that the void location will be found in the proper road position. This system is called a positioning system (*1*).

BORE HOLE CAMERA

The BHC system is shown in Figure 5. It consists of four parts, the video probe, the counter roller insertion device, the microprocessor-based control unit, and the diamond-tipped core boring equipment.

SINKHOLE DETECTION METHOD

After the road to be surveyed has been determined, the following steps of the primary and secondary surveys should be followed. This method is shown in flowchart form in Figure 6.

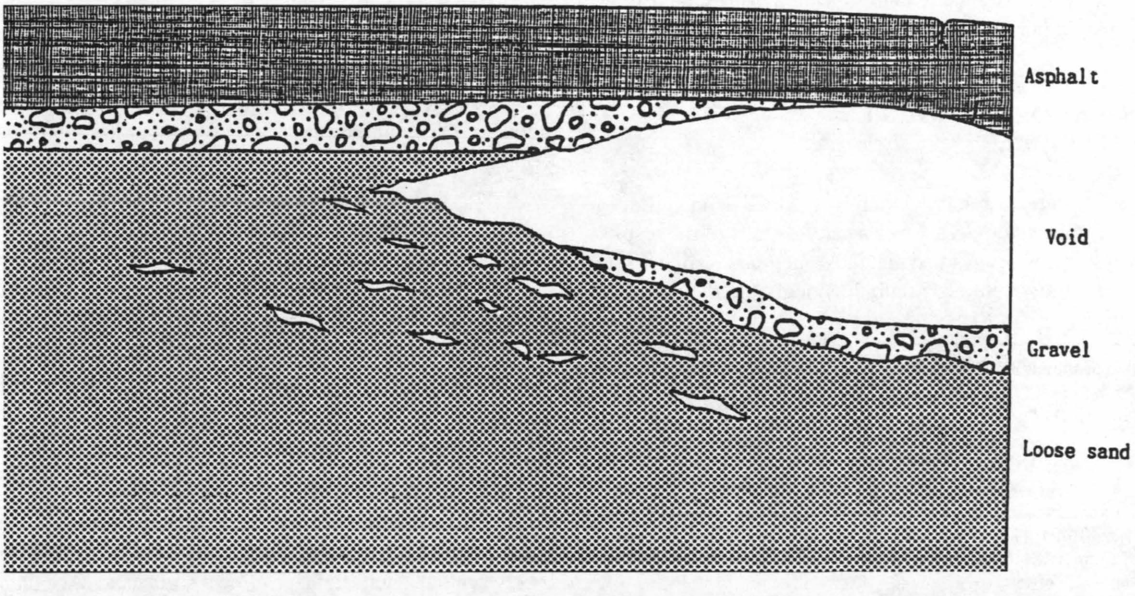


FIGURE 2 A typical subsurface void in the actual and formative states.

FIGURE 4 Positioning system orientation showing location and field of view of cameras.

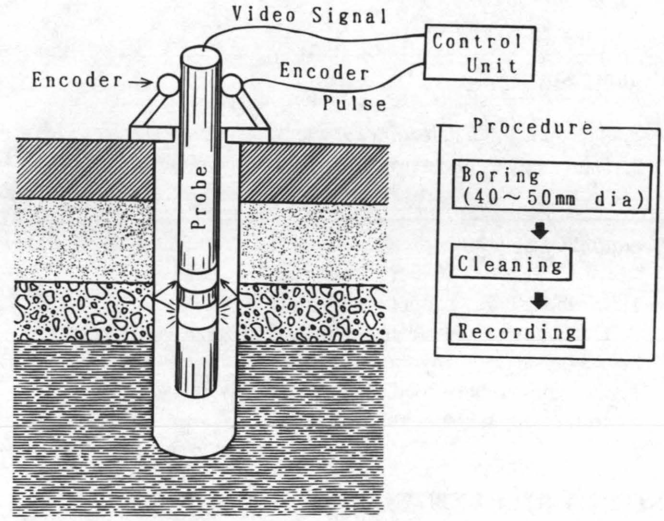


FIGURE 5 Drawing of BHC probe during data acquisition process.

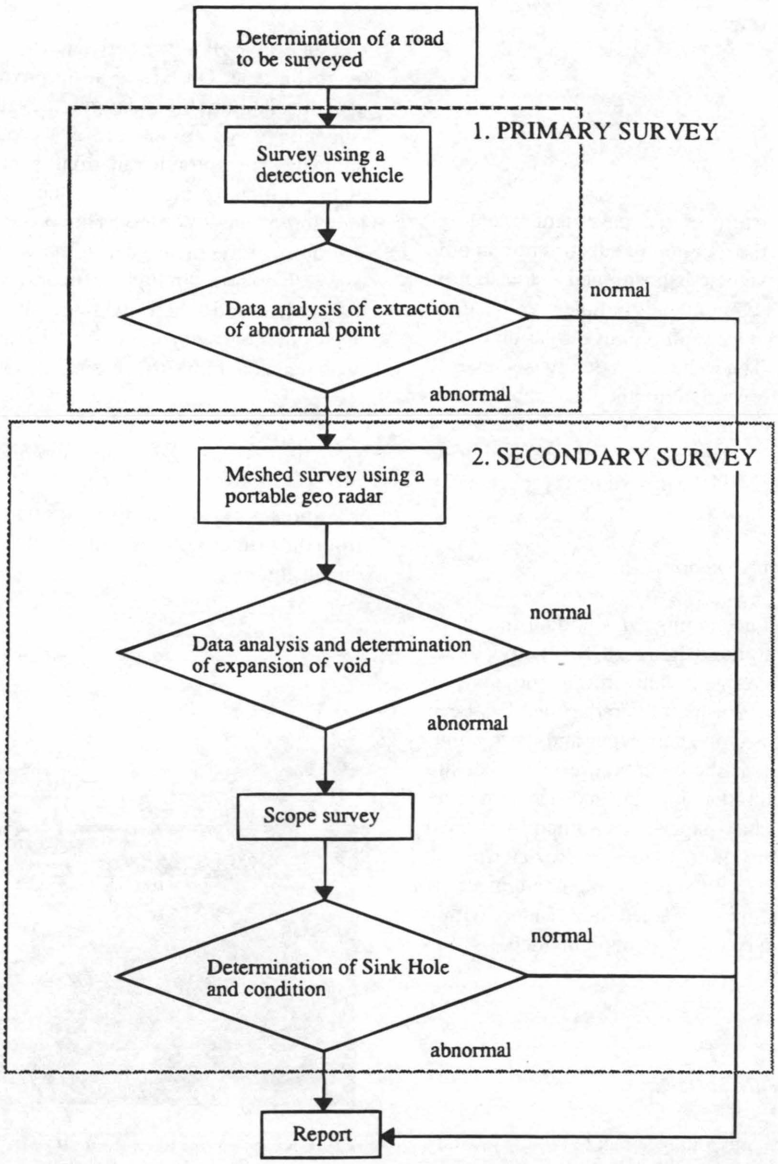


FIGURE 6 Flowchart of detection method.

Primary Survey

1. Survey using a detection vehicle.
2. Data analysis and extraction of abnormal point.

Secondary Survey

1. Meshed survey using portable radar gear.
2. Data analysis and determination of cavity dimensions.
3. Scope survey using the BHC system.
4. Determination of road subsurface cavity and condition.
5. Report to pavement engineer.

STEP-BY-STEP EXPLANATION OF METHOD

Determination of a Road To Be Surveyed

The determination of the road to be surveyed is made by the road authority. The selection criteria is ordinarily based on visually detected pavement distress or surface anomaly.

Primary Survey

Survey Using a Detection Vehicle

In the first look at the substructure of the pavement, the low-frequency radar vehicle detects the location of substructure anomalies such as voids. The survey vehicle is positioned at the start of the target lane segment, the GPR equipment is initiated, verbal cues are inserted onto the eight-track tape, and the investigation of the pavement substructure begins. The vehicle gradually achieves a speed of 20 km/hr and moves forward along the designated route. As the completion of the lane segment is achieved, the machinery is placed on standby mode, the vehicle is turned around and positioned to survey the opposite lane, and the procedure is repeated (*2*).

Data Analysis and Extraction of Anomalies

After the field survey has been accomplished, the data that have been acquired are turned over to the office staff for the post-data acquisition analysis. The storage media delivered to the analysis crew are the roll of chart paper on which the radar data has been recorded (a sample of a GPR trace on chart paper and its relationship to the position of the vehicle is shown in Figure 7), the backup 8-track magnetic tape that contains the radar and audio information, and the 8-mm videotape. The chart paper is examined by trained readers for examples of anomalies. If no anomalies are determined, the report is made and delivered to the pavement engineer. If abnormal points are determined by the trained data readers within the target pavement, the secondary survey is implemented.

Secondary Survey

Meshed Survey Using Portable Radar Gear

The field crew returns to the site previously subjected to the primary survey. Subsurface anomalies are located using the video and linear feet data, as well as the verbal cues and radar data from the 8-track magnetic tape. On arrival at the investigation site, the field crew uses special portable radar gear developed for the purpose of void detection to determine the exact parameters of the subsurface anomaly. The portable radar unit is passed over the target area and as the borders of the void are located, spray paint determines the location of these borders. This process is shown in Figure 8. The operators of the radar gear in the vehicle (the comfortable interior of which is shown in Figure 9) transmit to the radar transducer operators when and where the anomaly border has been detected by means of a two-way radio. In a short time, the subsurface void has been mapped with surface-applied spray paint.

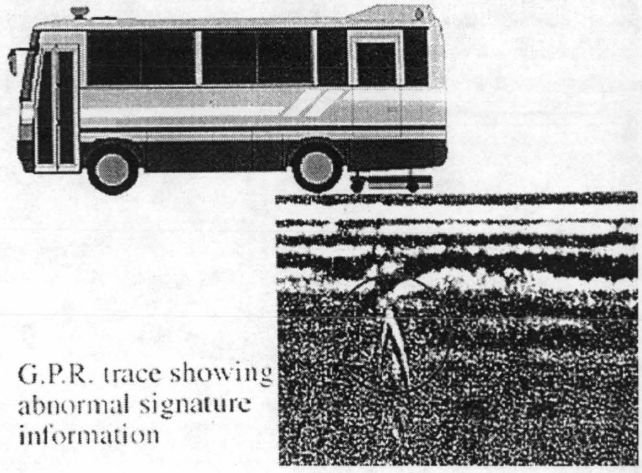


FIGURE 7 Detection vehicle with GPR trace juxtaposed showing orientation of data acquisition sequence.

Data Analysis and Determination of Cavity Dimensions

This process is similar to the previously noted data analysis step from the primary survey, but special care is taken to determine void dimensions.

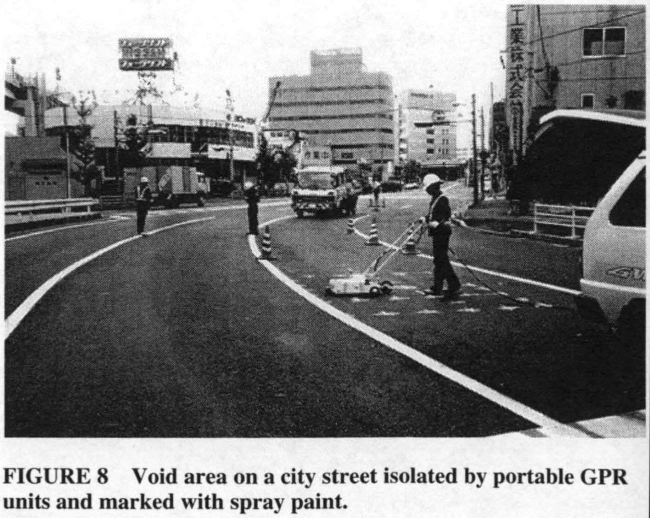


FIGURE 8 Void area on a city street isolated by portable GPR units and marked with spray paint.

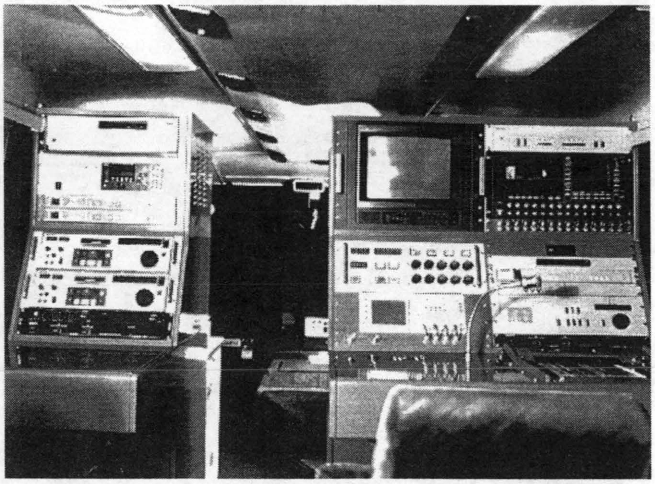


FIGURE 9 Interior of vehicle showing operator controls and data acquisition monitoring equipment.

Scope Survey

The common method for confirming the presence of a void is to cut and fill, but this method destroys the in situ condition of the possible void and does not allow the pavement engineer to know the true nature of the void. To perform the scope survey, a 40-mm hole is bored. After the bore hole has been drilled, the hole is cleaned with water and then vacuumed to remove any mud left over from the boring process. After the bore hole has been cleaned, the counter roller is positioned over the hole. The probe is then lowered into the hole. When the video portion of the probe descends just below the surface of the hole, the camera controller is activated and then the speed regulated descent of the probe begins. As the probe travels down the bore hole, the high resolution video equipment shows exactly the layer thickness, material composition, and void location, as shown in Figure 10. After data acquisition, the probe and the counter roller are removed. The hole is then repaired with a fast-cure concrete. The length of activity is about 45 to 55 min as opposed to 4 to 5 hr for cut-and-fill methods, which saves labor hours and driver inconvenience (*3*).

Determination of Road Subsurface Cavity and Condition

In this secondary survey, the planar expansion of the cavity is determined through the previously noted mesh survey investigation. Mesh survey and horizontal information is confirmed by the previously noted scope survey method.

Report to Pavement Engineer

Previous methods of reporting included excess amounts of data that posed a problem to the pavement engineer because they were difficult to read and interpret. The new reporting system that is currently being employed consists of the following components:

- Raw data. The actual field data are turned over to the pavement engineer, which includes the video and the magnetic tape record. These data are labeled with appropriate dates and lane identification.
- Printed report. Only those areas of the surveyed portion that include actual voids or suspected voids are included in the written report, which is designed to be easily read by the pavement engineer.
- Data base report. The same data are also prepared for easy data input into the pavement engineer's pavement management data base. More emphasis at this stage is placed on preparing the data for integration into the larger network.
- Summary report. The data are additionally compiled into an annual reporting format that allows the pavement engineer to see the long-term trend of void location, frequency, and size. This information allows the pavement engineer guidance to plan future surveys.

ACTUAL FIELD INSPECTION RESULTS USING THE DEVELOPED TECHNOLOGY

From November of 1990 to December 20, 1993, the total lane length surveyed by this method was 1,635 km. This survey detected a total of 212 possible sinkholes and, on investigation, 191 confirmed sinkholes were located in the pavement substructure, which had not yet migrated to the surface to cause a visible pavement failure. The remaining 21 areas that were identified as possible void areas contained buried wood, concrete blocks, or crushed concrete, which produce a GPR signal similar to a GPR void signal. All target areas were cut open and the existence of the voids or wood or concrete was confirmed.

Void Detection

1. Size of void. This detection system has enabled investigators to detect the development of underground voids. Figure 11 presents the size (expansion, thickness, volume) of detected voids and indicates the conclusion that 60% of the voids detected were less than 3 m^2 in area and less than 50 cm in thickness. The largest detected void was more than 9 m^2 and 2.8 m thick (approximately 25 m^3).
2. Location depth (the position of the top of the void and characteristics of pavement structure). A large percentage of the detected voids were located in a position with the depth of the top of the void less than 70 cm from the pavement surface and were positioned in or directly below the upper layer of the road bed. Additionally, the bottom of most pavements affected by voids showed sagging.
3. Rate of occurrence. The roads tested were those that had a history of detected voids in the past or that showed a possibility of developing a void condition. In this sample, which does not apply to all of the national and prefectural roads, voids were detected at least every 1.3 road kilometers (every 7.7 lane km) in the metropolitan area.
4. Causes. As soon as a void was detected, a repair was made. In about 30% of these cases, it was possible to determine the cause immediately, such as a broken rainwater conduit, a sewer pipe, or an empty pipe no longer in use. Based on void detection surveys conducted so far in the metropolitan area, where there is much underground pipe and construction, it is suspected that these underground objects and their method of installation are directly related to the development and existence of voids as shown in Figure 12. Corrosion of sewers by sulfur gas gradually causes sewer line failure, which can initiate a migrating void pocket, and large structures such as subway tunnels produce constant vibration, which contributes to the initiation of void pockets. Further, as a void migrates

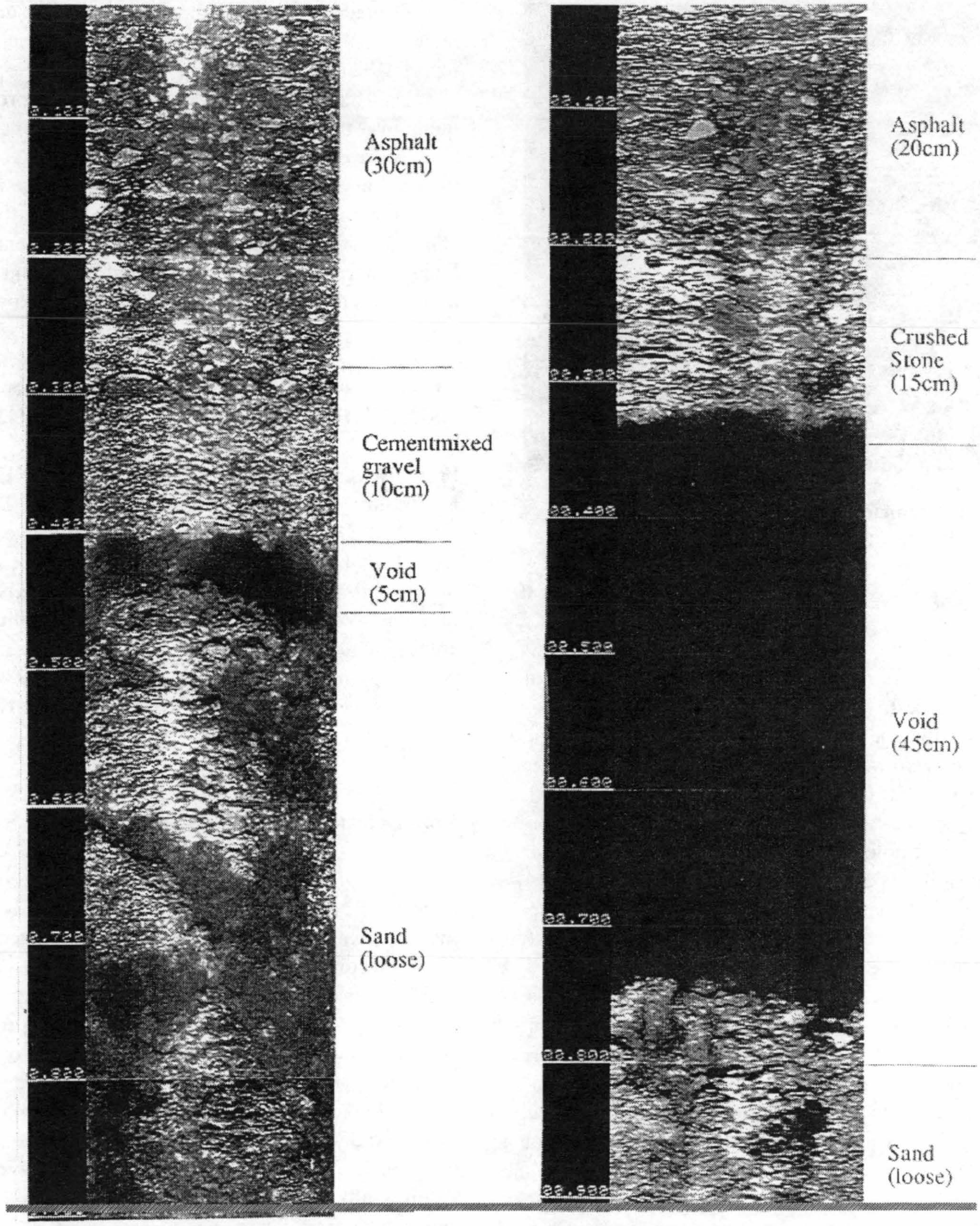


FIGURE 10 Sample of BHC records showing material composition and substructure configuration.

upward through the complex lattice-work of subsurface utilities infrastructure, the support of these conduits is undermined, thereby contributing to their possible failure.

Survey Result from Road Offices in Tokyo Ward

Tokyo consists of 23 ward offices. The annual number of sinkholes is collected by direct contact with area-responsible pavement officials. As a result, the average number of sinkholes is 100 holes per ward office per annum. This makes the total amount of pavement failures caused by voids per year over 2,000 in the Tokyo area. The identification of 212 possible voids and subsequent confirmation of 191 voids before the pavement failure stage represents 191 possible transit accidents avoided. With the continued application of the system, it is hoped that the ratio of actual pavement failures caused by voids, and voids detected before pavement failure, will shift in favor of prior detection.

Investigation of Mechanism of Sinkholes

From the experience gained in site survey result analysis, the following mechanical nature of sinkholes are thought to exist. The migration of the loose sand begins around a buried object forming an air pocket. From the time of void formation, the migration of the

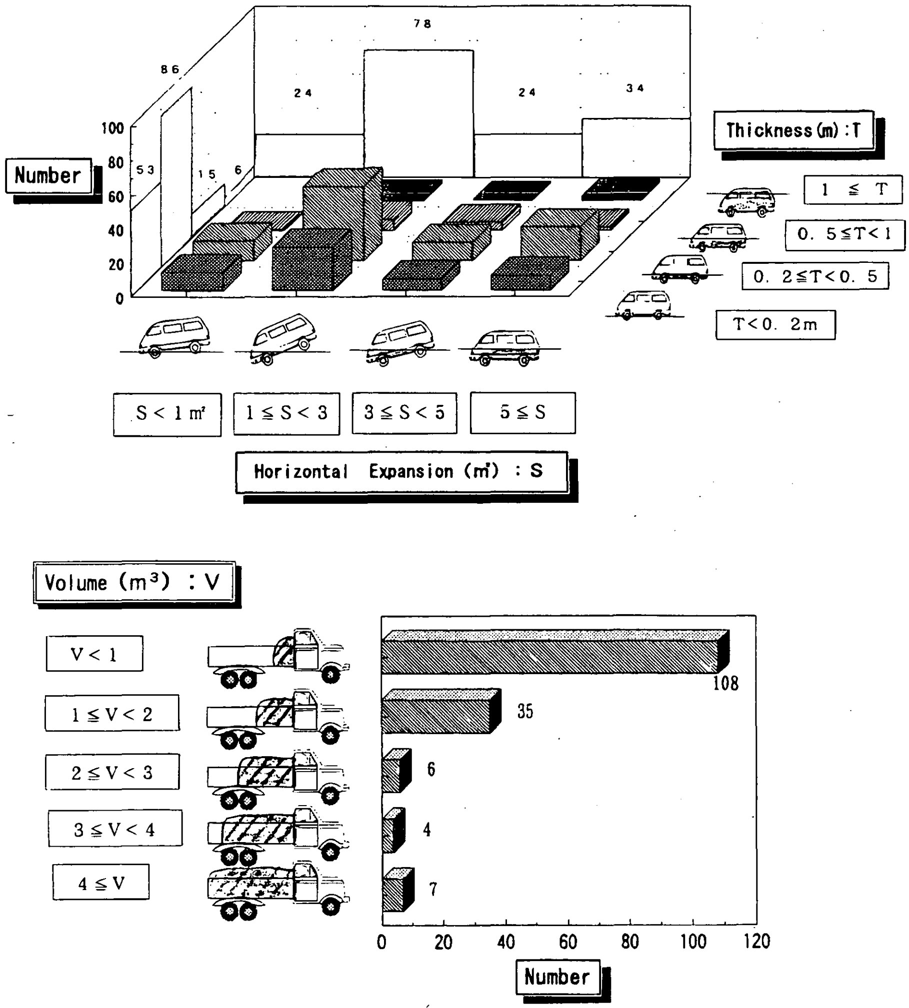


FIGURE 11 Condition of void development.

air pocket moves upward as the ceiling of the pocket falls to the floor of the pocket, thereby leaving fresh ceiling exposed. This process repeats itself until the resisting subsurface of the pavement is encountered. In a cold pavement condition, the load-bearing stress of the pavement may be sufficient for the vehicle support surface to continue to perform normally and not fail, but in hot weather, the heat of the sun causes the asphalt to become soft and the load-bearing stress capability of the pavement is lowered. The pavement then becomes subject to the lack of support caused by the migrated void and pavement failures that have been latent in cold weather reach the critical point of the failure curve as the weather—and hence the asphalt—becomes warmer, as shown in Figures 2 and 13.

Test Field Data

To confirm the above theory of void migration, ice was buried between gravel and a sand phase in a test field. Soon after soil-compacted burial, the ice melted and created an artificial void in the layer between the sand below and the crushed gravel above. The artificial void was monitored over a 2-year period, and the artificial void migrated upward to the pavement substructure as predicted. By this means, the process of void movement was confirmed. This movement through migration process was confirmed by periodic monitoring using GPR and the BHC site surveys.

CONCLUSION

The Developed System

The combination of the three equipment systems, the void detection vehicle, low-frequency GPR, and the BHC, make it possible to realize an effective void detection method, increase the safety level, and keep the traffic flow smooth. BHC survey results, investigation of sinkhole accident records, and test field investigation are clarifying the mechanical nature and process of void occurrence and subsurface pavement failure.

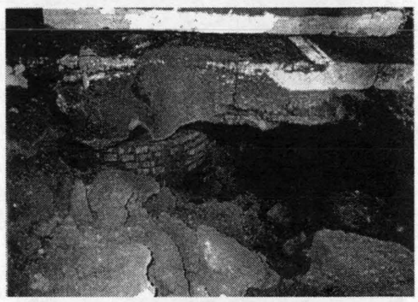
Future Improvement

The Ministry of Construction has contracted for extensive void surveys using the new vehicle over a 5-year period. During this period, all national roads in the Tokyo area will be surveyed. This will provide the pavement engineers with a broad overview of the road sit-

Condition of Void

Size of Void
(L 3.3 m x W 3.2 m x H 2.3 m)

Cause:
The cause of the void is not clear, but numerous underground constructions were noted such as subway lines, water pipes, electrical conduits, sewer pipes, etc.



Condition of Void

Size of Void
(L 3.0 m x W 3.0 m x H 1.0 m)

Cause:
It appears that a broken link of underground sewer pipe causes a leak of sewer water which erodes the soil.

Condition of Void

Size of Void
(L 2.5 m x W 3.0 m x H 0.5 m)

Cause:
The connector of a rainwater drainage pipe broke causing the soil to be eroded by rainwater runoff.

FIGURE 12 Photographs showing excavation of detected voids.

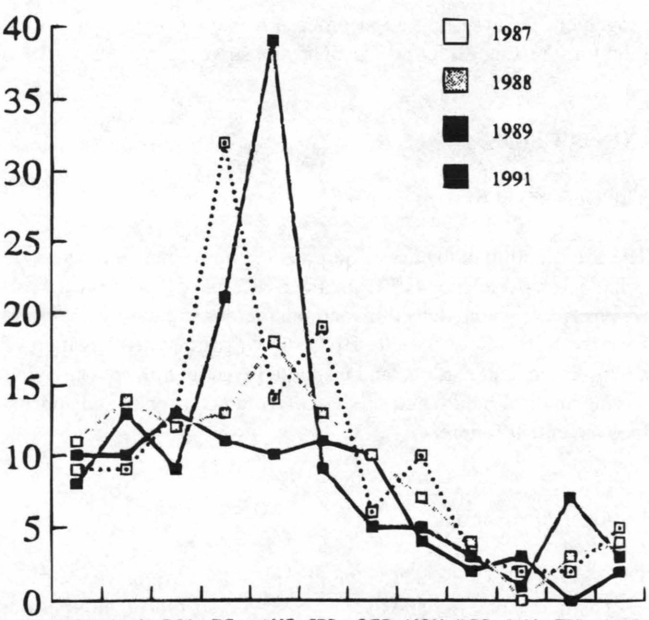


FIGURE 13 Annual distribution of sinkhole accidents reported in a typical Tokyo ward office.

uation, void frequency, and it will allow the determination of areas that are chronic problem areas. These trouble spots will be investigated with more frequency in an attempt to determine and solve the structural problems that cause repeated void formation. Ongoing investigations about what kind of repair material and method will be most effective for the repair of sinkholes are being conducted by the Ministry of Construction together with Public Works Research Institute. There is a feeling of confidence that these measures will cause an overall increase in road safety and driver comfort in Japan.

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