# DESIGN, CONSTRUCTION AND MANAGEMENT OF AIRPORT PAVEMENTS ON RECLAIMED GROUND

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## ABSTRACT

In Japan, airports must be constructed far from urban areas as there are few large flat sites, and must sometimes even be constructed on land reclaimed from the sea. This causes several problems for the pavements of airports. First, the water table is generally high, causing severe damage to pavements when heavy aircraft loads are repeatedly applied. Second, the vertical stress acting on the subgrade is higher than normal as a stiff subgrade cannot be obtained. Third, the differential settlement that often results, might require rehabilitation in the future. Other problems might also arise.

This paper describes the design, construction and management of airport pavements, and then explains the present study which examined the influence of the rough runway profile on both the pilots' operation ability and the pavement structure.

The current method of airport pavement construction is as follows. The influence of groundwater on the asphalt pavement is quantified through laboratory tests and field experiments. Reduction of the design CBR on the subgrade, use of asphalt stabilized material for the base, and installation of a drainage system surrounding the pavement are applied to design and construct water-resistant airport pavement. To decrease the subgrade vertical stress, use of the sandwich type asphalt pavement which introduces a stiff subbase directly on the subgrade, is studied. If differential settlement of the ground occurs, concrete pavements will suffer severe damage, in which case, reinforced concrete precast slab pavement with a cotter joint system is introduced to repair the damaged slabs. Furthermore, prestressed concrete pavements and the lift-up rehabilitation method are also used for adjusting settled pavements.

The present study on the rough runway profile is conducted as follows. Longitudinal profiles of pavement are measured using a profilometer mounted in a vehicle and combined with the Global Positioning System at normal vehicle speed. The profile data obtained at an airport runway on reclaimed ground are analyzed with conventional spectral analysis and computer simulation of the response of a large aircraft. Finally, the pilots' operation ability and passengers' comfort are analyzed, and then roughness criteria for runways and taxiways are determined. In addition, loading characteristics of moving aircraft and dynamic response of airport pavements to aircraft load are studied.

**KEY WORDS**

AIRPORT PAVEMENT / RECLAOMED GROUND / DESIGN / CONSTRYCTION / MAINTENANCE / MANAGEMENT.

## 1. INTRODUCTION

In Japan, airports must be constructed far from urban areas as there are few large flat sites, and must sometimes even be constructed on land reclaimed from the sea. Tokyo International Airport is a typical example: the ground was built utilizing waste soil deposits in Tokyo Bay and its condition is extremely poor. A representative soil profile is shown in Figure 1. Soil types are classified into two: those deposited in the Diluvium time and those in the Alluvium. On this natural ground, various kinds of soils such as waste soils and debris produced at urban construction sites have been placed[1].

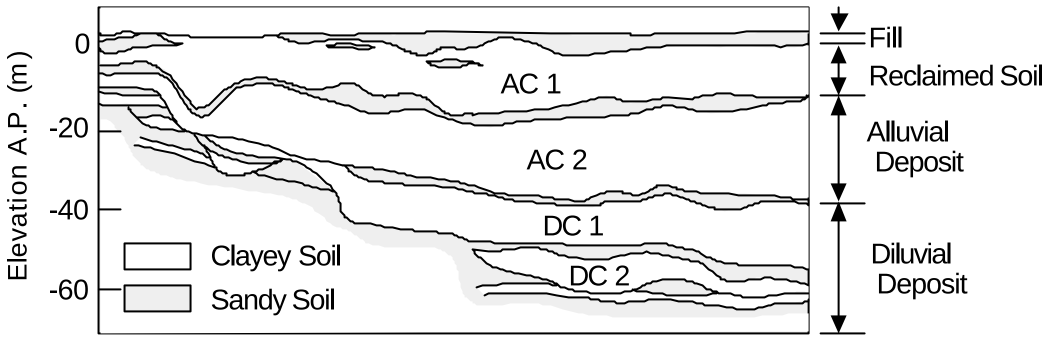



Figure 1 Representative soil profile

This causes several problems for the pavements of airports. First, the water table is generally high, causing severe damage to pavements when heavy aircraft loads are repeatedly applied. Second, the vertical stress acting on the subgrade is higher than normal as a stiff subgrade cannot be obtained. Third, the differential settlement that often results, might require rehabilitation in the future. Other problems might also arise.

Since such sites generally have a high groundwater table, not only the subgrade, but also the base course could be below the water table in some pavement areas. Pavement deteriorates rapidly under repeated traffic loading in a moist condition where water has infiltrated into the subgrade and base. This deterioration appears as potholes, heaving, cracking, roughness, and similar faults. To solve the problems, measures for not only pavement structures but also materials were considered.

As aircraft are heavier than automobiles, their influence reaches deeper into the pavement. On reclaimed ground, a stiff subgrade cannot be obtained, so special countermeasures to reduce the vertical stress on the subgrade must be taken. Instead of a thicker pavement, the so-called "sandwich" pavement was adopted from both engineering and cost reasons. In this pavement type, the vertical stress acting on the subgrade is reduced by introducing a stiff subbase directly on the subgrade.

Severe ground settlement and some differential settlement is unavoidable as full consolidation prior to constructing airport facilities would take too long. This was the case at

Tokyo International Airport, and repair works must be conducted. If pavements follow the settlement of subsoil, then the surface gradient of the pavements will exceed the specified value, whereas if the pavements do not follow the settlement, then cracks and joint faults will occur. As a thin concrete overlay is not entirely reliable for concrete pavement, precast concrete slab pavement, which has a relatively small slab size, was used for the reconstruction work. In addition, the lift-up method of concrete pavements was used. For such lift-up work, a prestressed concrete pavement is the only pavement type that offers sufficient flexibility of pavement and the weight of concrete slabs, as far as the capacity of jacks and the interval are concerned.

Rough pavement profiles affect not only the operation ability of pilots but also the response of pavement to aircraft, so in this study we examined the profiles quantitatively. Longitudinal profile measurements were carried out on the runway of an airport on reclaimed ground using a newly developed non-contact type profilometer, which was mounted in a vehicle and combined with the Global Positioning System. It was capable of acquiring the profile of the pavement surface at intervals of 10 mm with an accuracy of ±1.2 mm by using a short wavelength at normal vehicle speed.

The measured profile data were studied by spectral analysis. In addition, the response of a large aircraft to the measured runway profile was simulated by computer. Vertical accelerations at the center of gravity of the aircraft were computed, the aircraft operation ability was analyzed and criteria for pavement profiles were derived. A method of calculating the dynamic response of the pavements against moving aircraft was also investigated.

## 2. DESIGN OF PAVEMENTS FOR HIGH GROUNDWATER CONDITIONS

Both laboratory tests and field investigations were conducted[2)].

### 2.1 Design of subgrade

CBR values are related to the modulus of elasticity. The degree of reduction of bearing capacity of a subgrade due to saturation can be quantified by the CBR values converted from the modulus of elasticity.

Moduli of elasticity for designing a subgrade are summarized in Figure 2. Since the materials used for the laboratory tests were not identical to those of the test pavements, differences between the two are significant. The vertical axis of this figure shows the ratio of the subgrade modulus to that for the unsubmerged case, while the horizontal axis shows the saturation ratio (i.e., the thickness of the submerged portion to the total thickness). The figure shows that the modulus ratio decreases as saturation increases. The modulus ratio drops to 95%, 90%, and 80%, when half, 2/3, and the entire subgrade is saturated, respectively. Thus, when designing the pavement structure, either the unsubmerged value assuming stabilization of the subgrade should be used, or the reduced strength caused by saturation should be used.

### 2.2 Design of base

The modulus of elasticity of the granular base changes with the groundwater level, as shown in Figure 3. The modulus of elasticity decreases to 90%, 80%, and 70% of the unsaturated values when 1/4, half, and all of the base is saturated.

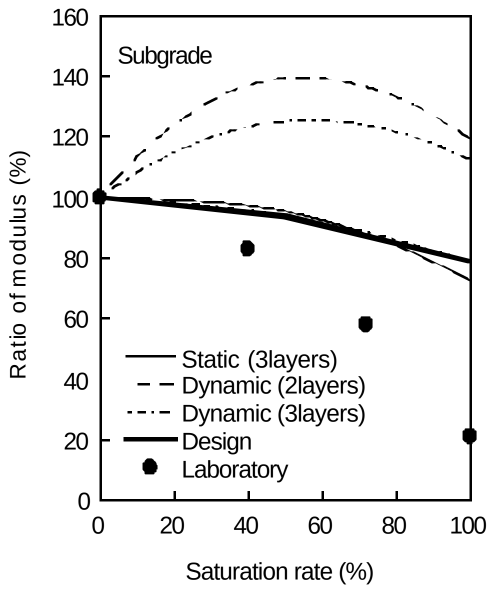



Figure 2 Modulus ratio of subgrade and saturation rate

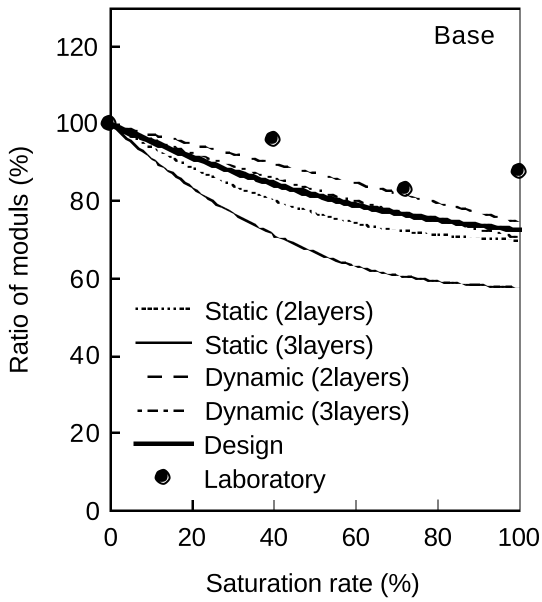



Figure 3 Modulus ratio of base and saturation rate

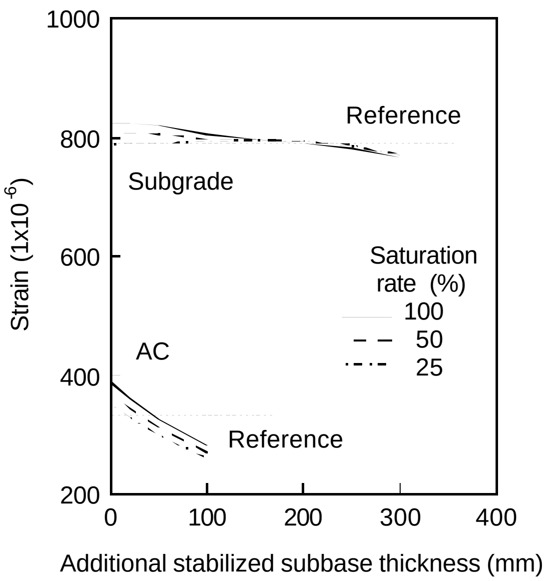



Figure 5 Reduction of strains due to stabilization

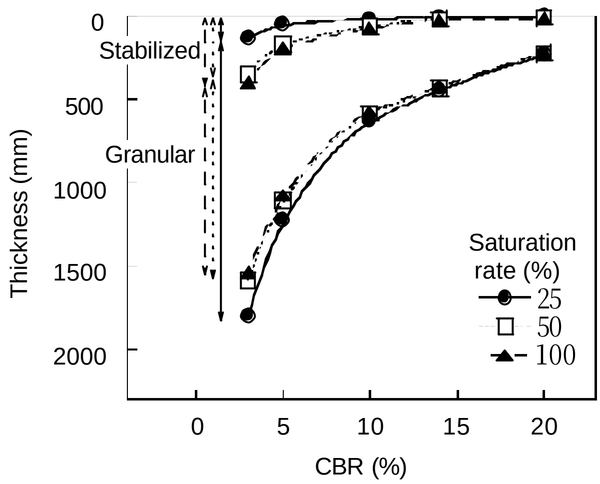



Figure 7 Design of subbase in submerged condition

The use of a reduced modulus of elasticity means that the load carrying capacity of the pavement is reduced, however, the load carrying capacity must remain almost unchanged even when saturated. As this issue is not addressed in the current structural design methods for airport pavements, a new design method must be developed.

The vertical strain at the top of the subgrade and the horizontal strain at the bottom of the asphalt concrete are generally used as indices for evaluating the structural condition of pavement, and were also used. Therefore, a submerged pavement structure that has strains equivalent to those in the standard pavement before submergence is structurally equivalent to the standard pavement before submergence. Increasing the thickness of granular layers cannot fully compensate for submerged conditions, so the subbase must be partly stabilized even if asphalt stabilized materials are used for the base course. The relationship between the asphalt stabilized subbase thickness and strain is shown in Figure 7 for the conditions described above. The subgrade and asphalt stabilized layer strains become equivalent to the reference strain by partial stabilization of the subbase. An asphalt stabilized subbase thickness of 200 mm is required based on the strain of the subgrade, and a thickness of 50 mm is required based on that of the asphalt concrete layer.

Similar calculations were made to obtain the thickness of the asphalt stabilized layer required to satisfy the criteria for both the vertical strains in the subgrade and the horizontal strains in the asphalt concrete layer. Figure 8 shows design curves of subbase thickness obtained by this method.

## 3. DESIGN OF SANDWICH PAVEMENT

The following procedure was used to determine the structure of sandwich pavement[3)]. First, a conventional asphalt pavement was designed in accordance with the subgrade CBR concept given in the current design manual. Then, an equivalent sandwich pavement structure was selected so that the subgrade vertical stress in the sandwich pavement became equal to that in the conventional pavement. In this process, a multi-layered linear elastic theory was employed. The procedure used to determine the sandwich pavement structure is described below.

In accordance with the current design manual for airport asphalt pavements, the conventional asphalt pavement was determined. To determine the sandwich pavement structures, the process by which the base course and the granular subbase are selected in order was used. As the base course, a cement treated material was selected (CTB).

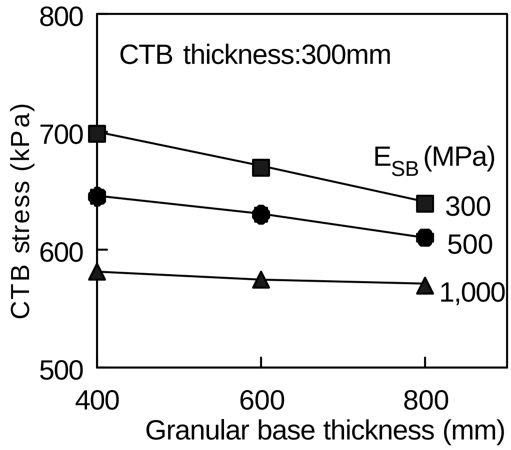



Figure 8 Tensile stress of cement treated base course

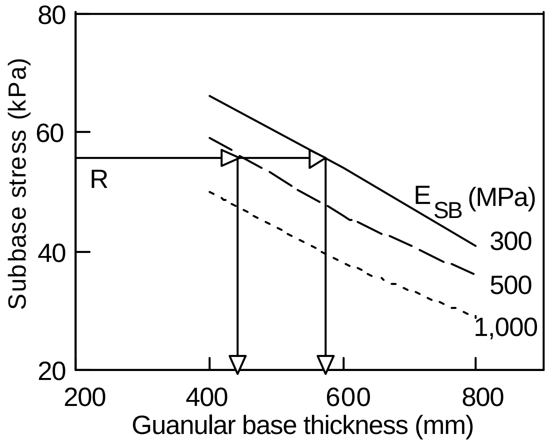



Figure 9 Vertical stress on subgrade

In order to prevent structural failure of the stiff layer, the maximum stress of CTB must be examined first. Figure 11 shows the stress of CTB with the thickness of 300 mm. It is clear that the stress of CTB decreases with an increase of the granular subbase thickness. A laboratory study of the fatigue characteristics of the material showed that the maximum stress of CTB is low enough to sustain the repetitive loadings.

Next, the granular subbase thickness must be determined in consideration of the vertical stress on the subgrade. Increasing the granular subbase thickness is an effective way to decrease the subgrade stress. By complying with the design principle that the subgrade stress in the sandwich pavement should be equivalent to that in the conventional structure (designated as “R” in Figure 12), the thickness of granular subbase can be determined.

## 4. REHABILITATION OF CONCRETE PAVEMENTS

### 4.1 Precast slab pavement

In concrete pavements, instead of placing concrete slabs in-situ which requires a long curing time, pavement using precast prestressed concrete (PPC) slabs which are manufactured in a factory has been used.

The conventional method of connecting laid PPC slabs is by the horn joint system, in which the slabs are connected by inserting arc-shaped steel bars from the surface of the slabs into arc-shaped plastic tubes cast into the concrete and grouting the gap between the tube and bar. This joint also makes it possible to replace and rejoin slabs simply by cutting the reinforcing bars and knocking the old bars and grout out of the tubes[4)].

PPC slab pavements with the horn joint system have been used at several airports in Japan. Some problems, such as pumping and faulting, have been observed over several years after construction, and the construction cost is also high.

To solve these issues, we studied reinforced concrete (RC) precast slab pavement using high strength concrete with the cotter joint system. The principle is to insert H-shaped wedges in both C-shaped jigs which are embedded in advance in the RC precast slabs as shown in Figure 13. The durability of both RC precast slabs and the cotter joint system was verified through experimental pavements. Then, the structural design procedure of the precast high strength RC slab pavement for airports was developed.

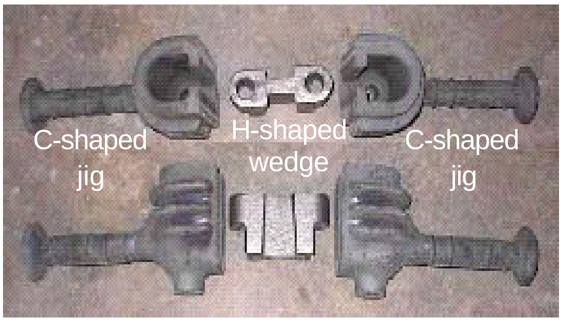



Figure 10 Cotter joint

### 4.2 Lift-up method of prestressed concrete pavement

The lift-up method of prestressed concrete (PC) pavement is executed as shown in Figure 14.

First, 160-mm diameter holes are cut in PC slabs with a core boring machine. Base course materials are excavated through the holes with a special boring machine and installation fittings for jacks are attached to the holes. Then, reaction concrete beds are placed and jacks shown in Figure 15 are fixed to the installation fittings. The PC slabs are lifted up by the reaction force of the jacks from the reaction beds. The void beneath PC slabs is grouted after the lift-up work[5)].

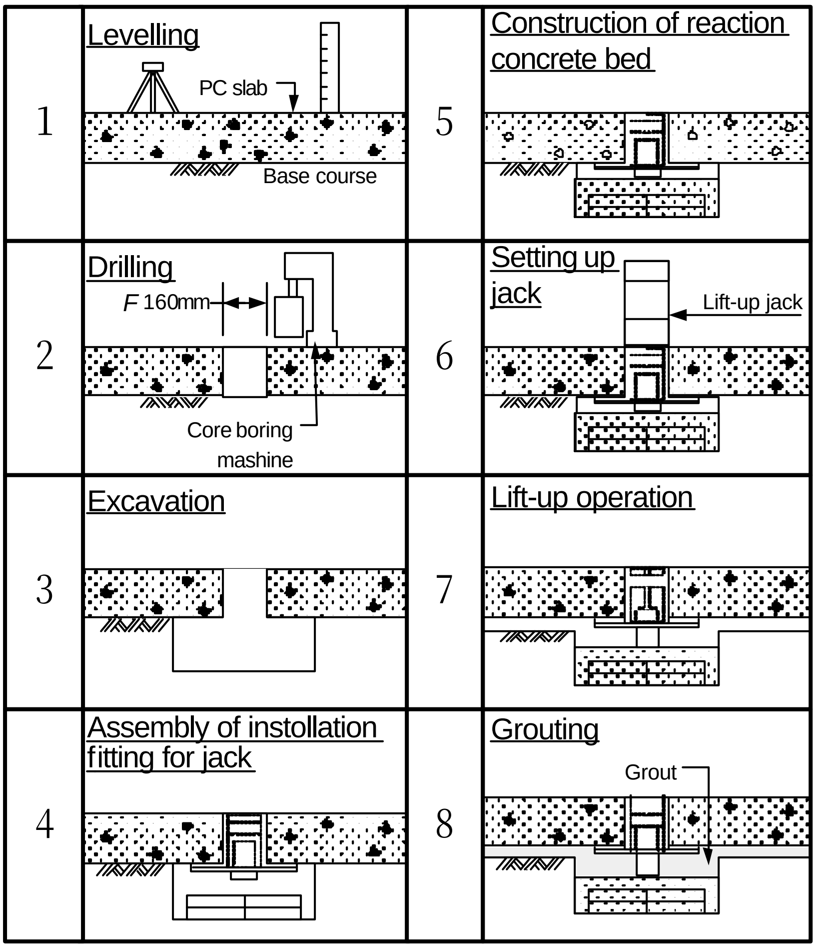



Figure 11 Lift-up method

Figure 12 Lift-up jack

The operation can be carried out quickly, precisely and safely by checking the pressure of the jacks and the lift-up heights by an automatic control system. The lift-up heights are displayed on a personal computer and drawn by the plotter in real-time at any stage from the start to the end of the operation. Thus, the lift-up work over wide areas can be controlled systematically.

## 5.MEASUREMENT OF RUNWAY PROFILE

### 5.1 Measuring equipment

The profilometer used in this study was a non-contact type which employs the sequential two points method to measure the profile. The response frequency of the laser distance meter is 4 kHz, and so covers 144 km/h when the measurement interval is 10 mm. With this measuring equipment it is possible to capture short wavelengths range down to 1 mm, but not long wavelengths, because the error is accumulated and considerable distortion is unavoidable at long wavelengths. To obtain accurate profile data at both short and long wavelengths, the Global Positioning System (GPS) was combined with the profilometer[6)].

The point positioning GPS is often used for satellite navigation systems without a fixed station and has an accuracy of 30 m or more. However, this accuracy was not sufficient for our study, so we used the real-time kinematics type GPS which has an accuracy of 2–3 cm in the vertical direction. The system acquired 1 elevation datum per second, which was processed in real time during measurement. Figure 17 shows the system schematically.

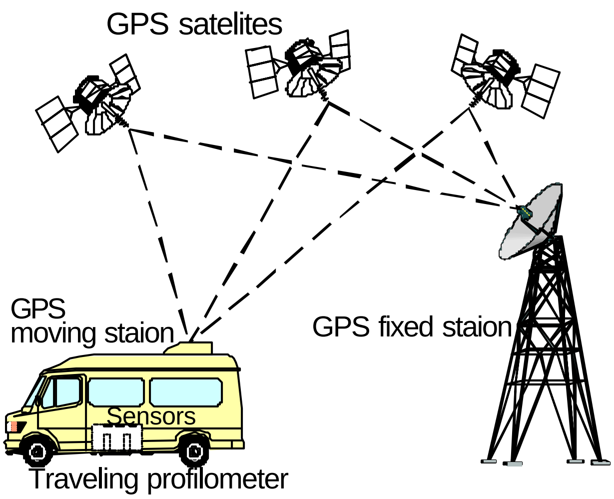



Figure 13 Schematic diagram of measuring system for absolute elevation

### 5.2 Measurement of absolute elevation

The runway profile at an airport runway on reclaimed ground was measured. Runway profile data was obtained on seven lines, each of which was 3,000 m long: the centerline, and pairs of lines at 1.92 m, 4.65 m, and 5.50 m either side of the centerline. The lateral positions of these lines were determined based on the tire patterns of a B747 aircraft. The profile was measured for all these lines in both directions, starting from the 34R side to the 16L side and starting from 16L to 34R, at a measurement speed of about 50 km/h for each line.

### 5.3 Results of runway profile measurements

Surface elevations of the runway pavement were determined by measuring the range of long wavelengths using GPS and the range of short wavelengths using the non-contact type profilometer as shown in Figure 18. Absolute vertical profiles were accurately obtained by combining these two data for a considerably long distance. The data were converted to the space domain and combined with short wavelength data obtained by the profilometer, since long wavelength data were obtained every one second by GPS in the time domain.

An example of the measured absolute vertical elevation is shown in Figure 19. The two measured profiles on both sides (34R and 16L) are completely consistent, with a standard deviation of error of almost zero.

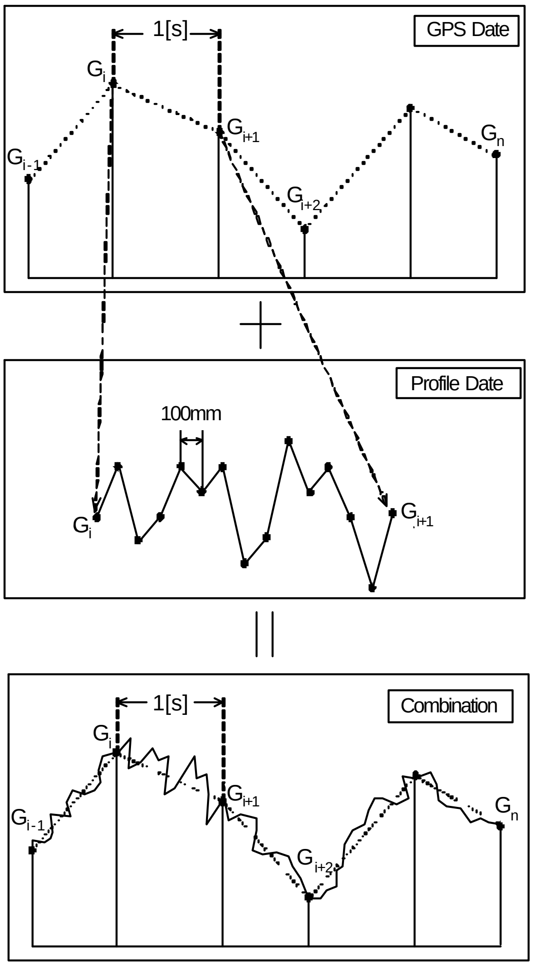



Figure 14 Acquisition of absolute elevation by combining profile data and GPS data

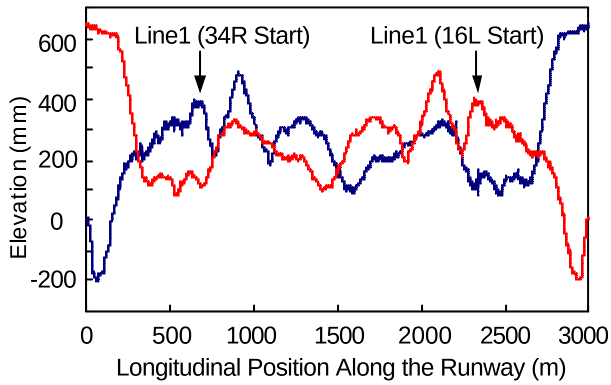



Figure 15 An example of measured absolute elevation

## 6. INFLUENCE OF RUNWAY ROUGHNESS ON AIRCRAFT OPERATION

### 6.1 Power spectrum density analysis

Power Spectrum Density (PSD) analysis was employed to evaluate the roughness of the runway pavement surface. The analyses were carried out for the long and short ranges of wavelength.

Figure 21 shows an example of calculated PSD for the 3,000 m long measured line 1. The German Engineer Association standard (VDI standard), which was originally developed for evaluating highway surfaces, was adopted as an index to compare the results of the two analyses as there are no standards for evaluating runway pavement surfaces. PSD is just under the 'very good' line. There was a very small difference in the calculated PSD among different measured lines, because the PSD is more affected by long wavelengths rather than local roughness or small distresses.

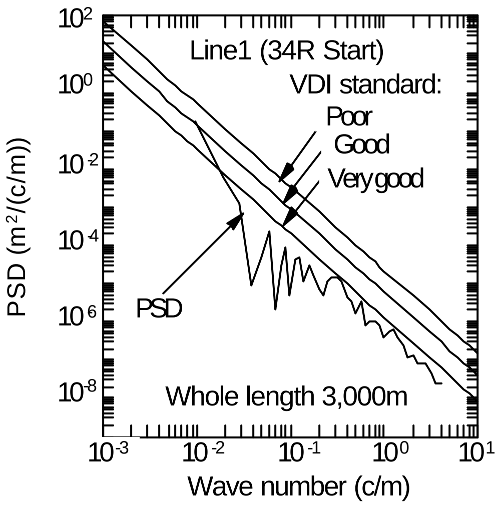



Figure 16 PSD for the whole length of runway at line 1

### 6.2 Simulation of aircraft vertical movement

Simulations of aircraft movement on the runway at takeoff and landing were carried out. The APRas software was used to simulate the vertical movement of aircraft. When retrieving profile data, APRas is able to calculate the aircraft accelerations at the pilot's station (PSA) and the center of gravity (CGA). Evaluation at PSA is very important when considering the operation ability of aircraft.

An example of simulated aircraft acceleration on line 4 at PSA and CGA is shown in Figure 22 for takeoff from 16L. When taking off, the amplitude of acceleration reaches a maximum at the speed of 50–100 knots.

### 6.3 Criteria for roughness evaluation

A vertical acceleration of 0.35 G for the aircraft dynamic response is used as the riding quality criterion for evaluating airport pavement roughness. Criteria for evaluating airport pavement roughness were assessed based on this criterion and the simulation results[7).

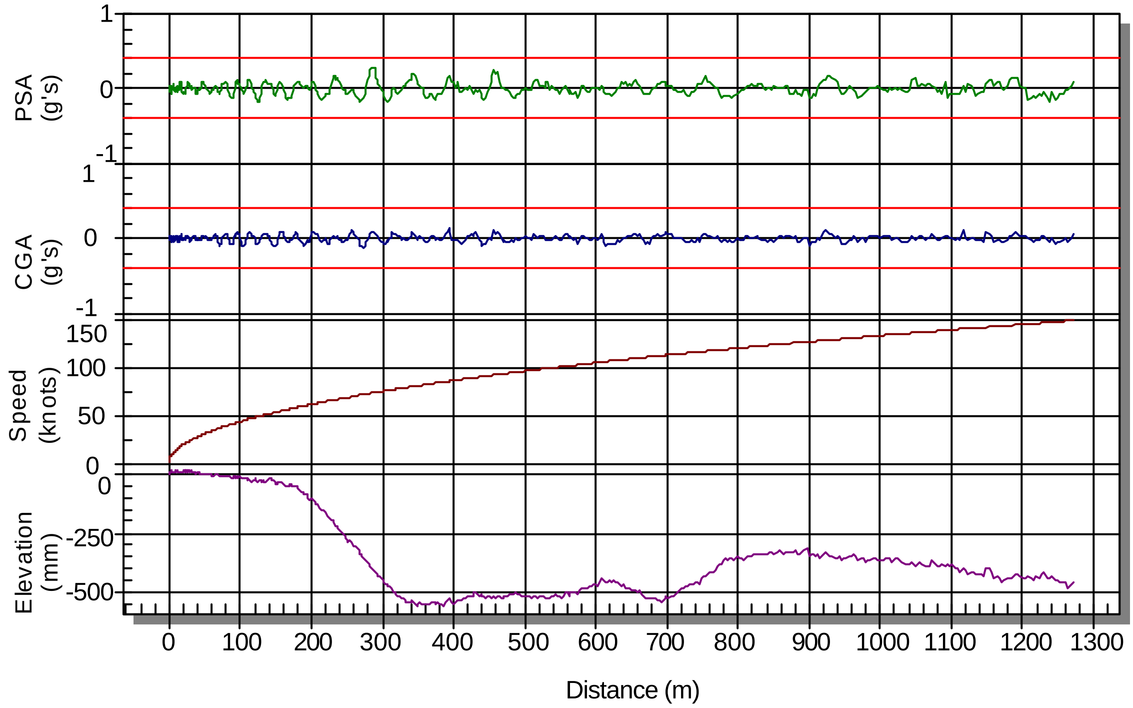
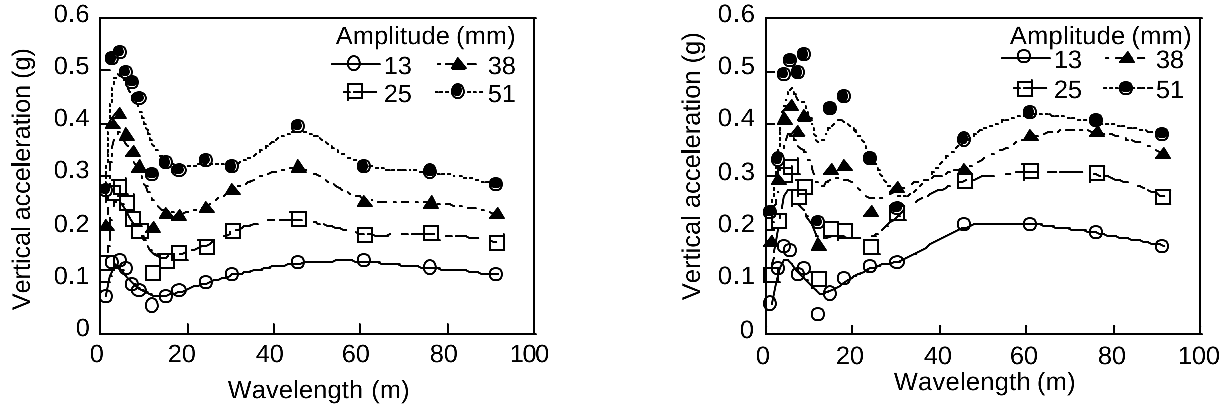


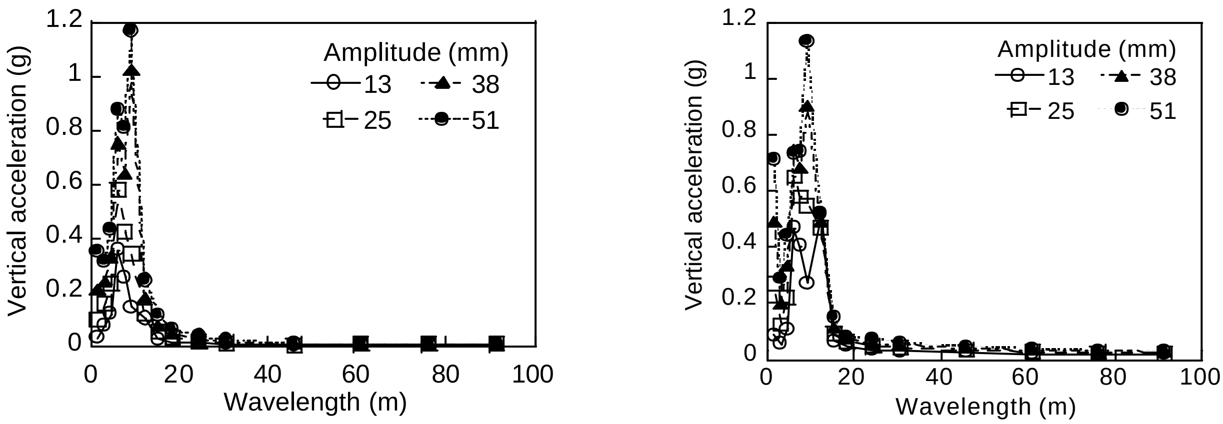

Figure 17 Simulated aircraft acceleration at takeoff from 16L




(a) Vertical acceleration of center of gravity at take-off

(b) Vertical acceleration of pilot station at take-off

Figure 18 Aircraft response on runway roughness




(a) Vertical acceleration of center of gravity when taxiing

(c) Vertical acceleration of pilot station when taxiing

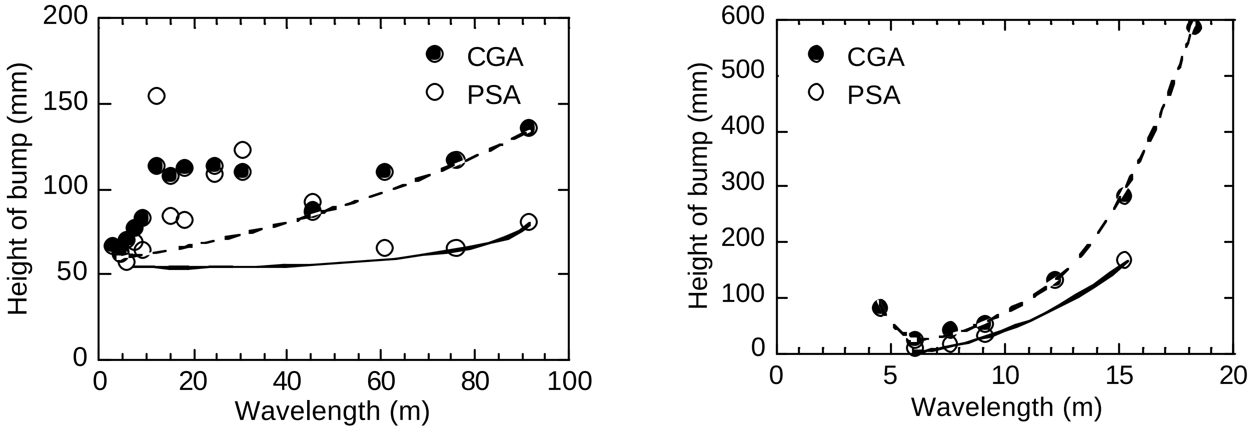
Figure 20 Aircraft response to taxiway roughness

From Figures 25 and 26 which show the representative maximum vertical acceleration at takeoff and taxiing, and from a comparison of the results and the criterion, the following were observed.

1) For aircraft taking off from a runway, amplitudes of pavement roughness of over 38 mm are intolerable. Amplitudes of 25 mm or less are tolerable regardless of the wavelength of the pavement roughness.

2) For aircraft taxiing on taxiways, the peak aircraft vertical acceleration generally exceeds the vibration criterion of 0.35 G at wavelengths below 12 m regardless of the amplitude. The peak vertical acceleration on the taxiway at both CGA and PSA is significantly higher than that for aircraft taking off from a runway.

Figure 27 shows the proposed evaluation criteria for runways (Figure 18 (a)) and taxiways (Figure 18 (b)), which are the envelopes over the simulation results at CGA and PSA, respectively. It is seen that criteria derived from the pilot station position are stricter than those from the gravity center position. The proposed criteria can be applied to actual pavement profiles because the aircraft response to continuous sinusoidal waves is more critical than to single or multiple bumps.




(a) Roughness criteria for runway (b) Roughness criteria for taxiway

Figure 22 Criteria for roughness evaluation

## 7. RESPONSE OF PAVEMENT TO MOVING AIRCRAFT

### 7.1 Finite element dynamic analysis

A 3D finite element program was developed in order to perform a comprehensive analysis of pavement behavior with an efficient method for detecting the elements subjected to the load of aircraft tires. Aircraft tire is treated as a moving distributed normal surface load. An 8-node isoparametric brick element is adopted for modeling the pavement. The dynamic response to moving aircraft wheel loads is investigated and the influences of moving load speed on the response are also studied[8].

The equation of motion of the finite element model for the pavement structure subjected to moving wheel loads can be expressed as

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{f(t)\} \quad (1)$$

with the initial conditions $\{\dot{u}(0)\}=\{0\}$ and $\{u(0)\}=\{0\}$, where $[M]$, $[C]$, $[K]$ are the mass, damping and stiffness matrices, respectively; $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the acceleration, velocity and displacement vectors, respectively; and $\{f(t)\}$ is effective external nodal load vector caused by moving wheel loads. The present analysis assumes the damping to be proportional to stiffness matrix, that is $[C]=a[K]$, where $a$ is the damping coefficient.

## 7.2 Basic description of problem

An airport pavement structure, which corresponds to the airport runway on reclaimed ground, subjected to moving wheel loads at constant speed, is considered. The pavement layer configuration is shown in Figure 29. Table 1 presents the material properties of the pavement layer, of which moduli were backcalculated from the FWD deflections. The damping is assumed to be proportional to stiffness, and the damping takes 0.5 percent of stiffness.

3D finite element meshes were generated to represent the pavement structure. The analysis volume had dimensions of 20 m long, 20 m wide and 10 m deep. Taking advantage of the geometric symmetry, one half of the 3D finite element mesh was generated to simulate the dynamic response of the airport pavement subjected to moving wheel loads, as shown in Figure 30.

The tire and pavement contact area is approximated by a rectangle $(0.4L \times 0.6L)$ and two semicircles with a radius of $0.3L$, in which $L$ is the total length of the loaded area ($L$ = 0.56 m). The total applied load for one gear of a B747-400 with 4 wheels is 910 kN, which results in a tire pressure of 1.35 MPa.

In the pavement design, the longitudinal strain $e_{xx}$ at the bottom of the asphalt concrete (AC) layer and the vertical compressive strains $e_{zz}$ at the top of the subgrade were used as the design criteria of the pavement. Accordingly, the results for surface deflection and $e_{xx}$ of the AC element along the gear centerline as well as $e_{zz}$ of the subgrade element along the pavement centerline are presented.

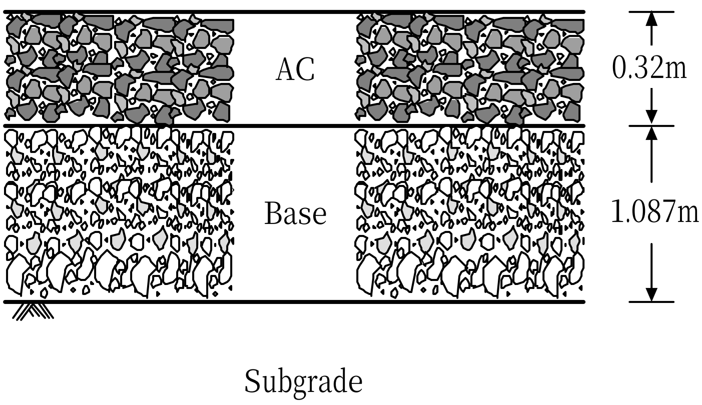



Figure 23 Pavement layer configuration

Table 1 Material properties of pavement layers

| Layer | Modulus (MPa) | Poisson's ratio | Density (kg/m$^3$) |
|---|---|---|---|
| AC | 4645 | 0.35 | 2300 |
| Base | 166 | 0.35 | 2300 |
| Subgrad | 125 | 0.35 | 1900 |

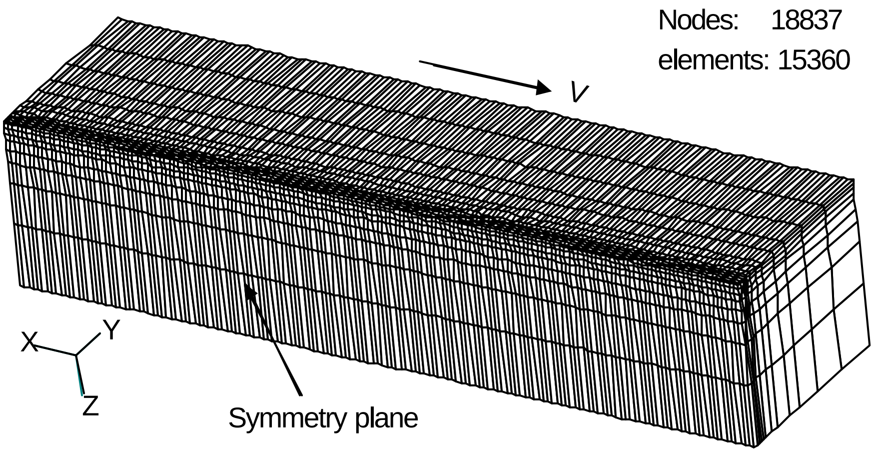


Figure 24 3D finite element mesh

## 7.3 Pavement response to a moving single axle load

A moving single axle load with a constant velocity $V$ = 10 m/s is considered to investigate the dynamic responses of airport pavement. Figure 32 shows the computed time history responses of deflection. It can be seen that the magnitude of surface deflection, shown in Figure 21(a), along with the center of the tire remains constant when the moving load is nearly 4.0 m apart from both ends of pavement, as expected. The dynamic deflection at the central point located in the centerline of the gear shown in Figure 21(b) reflects the fact that the influence region of a moving load is located in the vicinity of the central point. This implies that the dynamic responses within the region of 4.0 m to 16.0 m are not influenced by the boundary conditions.

The typical time history of strain for a single axle load moving at a speed of 10 m/s is shown in Figure 33. For the longitudinal strain response at the bottom of the AC layer, there exist two stress states, tension and compression. The maximum tensile and compressive strains are 243 and $42\times10^{-6}$ respectively. These phenomena might result in the cracking of pavements. In contrast to the longitudinal strain, the transverse strain remains tensile, and the maximum tensile strain is $162\times10^{-6}$. For the vertical strain at the top of subgrade, it remains in the compressive state, and the maximum strain is $264\times10^{-6}$. These figures also show that the dynamic responses are slightly lower in magnitude than the static responses, as expected.

## 7.4 Influence of moving speed

Figure 36 shows the relationship between the surface deflection histories and the moving speeds. From the figure, as the moving speed increases, the deflection decreases and the more fluctuations occur in the beginning. There is no substantial difference in the surface deflection when the moving speed increases; only a reduction of 5 percent in the surface deflection takes place when the moving speed increases from 10 to 40 m/s.

Figure 37 shows the relationship of the strain histories for the AC layer and subgrade with the moving speeds. From the figure, the longitudinal strain at the bottom of the AC layer decreases as the moving speed increases. The reduction in strain for the AC layer is quite substantial as the moving speed increases: a reduction of 20 percent in the strain for the AC layer takes place when the moving speed increases from 10 to 40 m/s. In contrast to the strain of the AC layer, the vertical strain at the top of the subgrade decreases very slightly even when the moving speed increases.

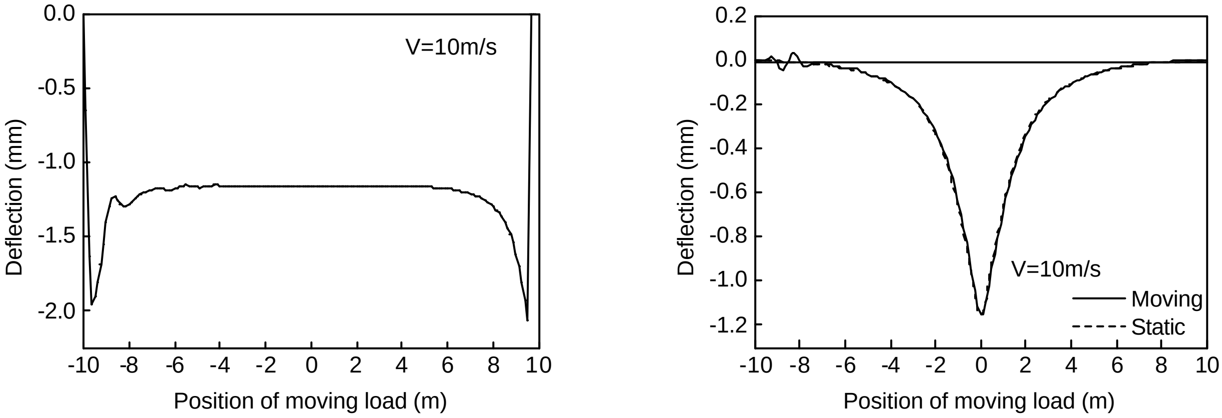



Figure 25  Variation of deflection histories induced by single axle

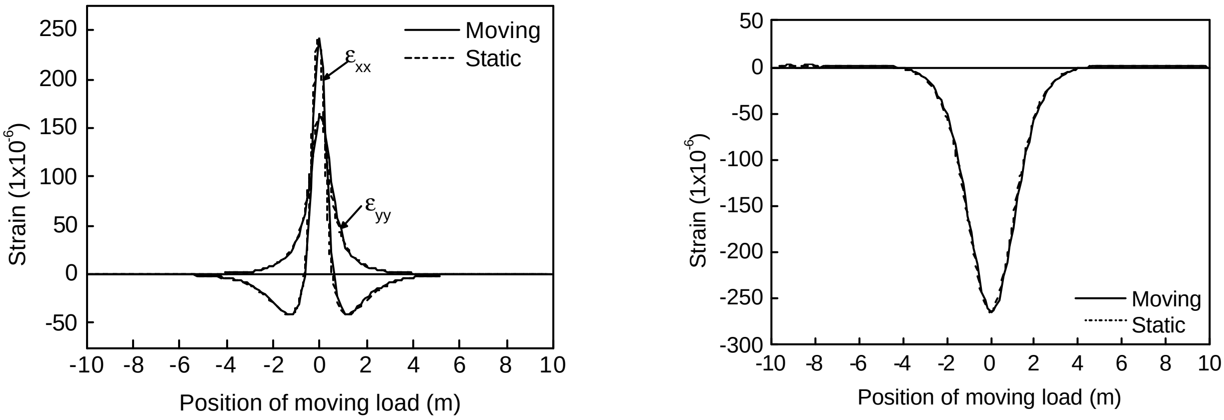



Figure 26  Variation of strain histories at central point induced by single axle

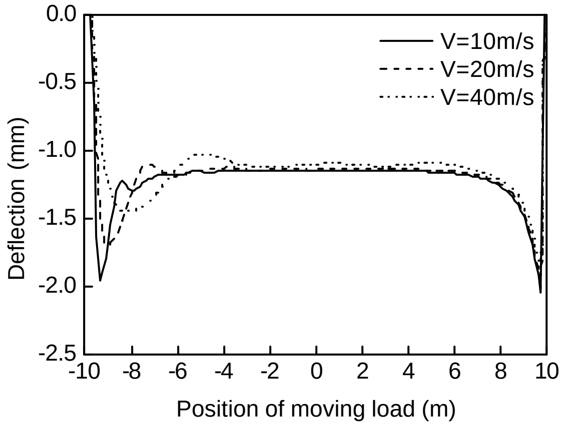



Figure 27  Variation of surface deflection history induced by different moving speeds

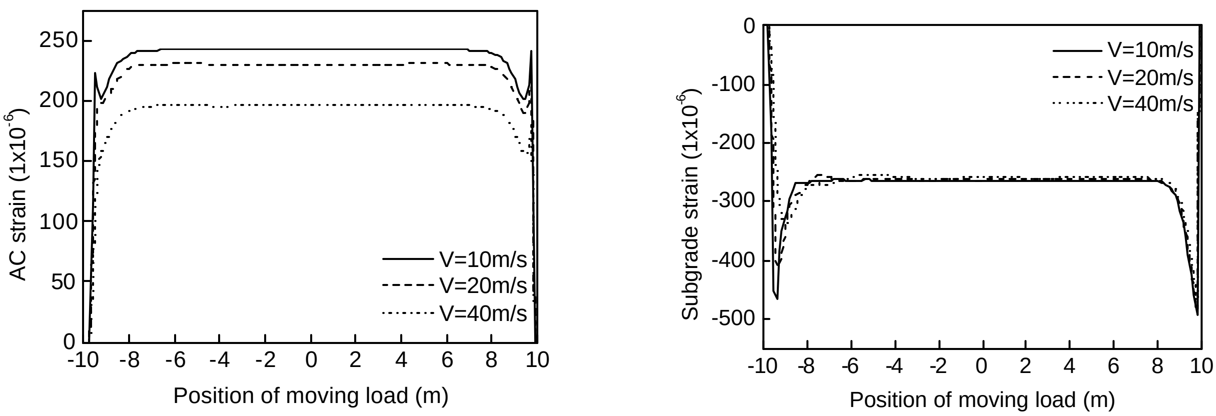



Figure 28  Variation of strain histories induced by different moving speeds

## 8. CONCLUDING REMARKS

This paper described the implementation of design, construction and management of airport pavements, and then explained the present study which examined the influence of the rough runway profile on both the pilots' operation ability and the pavement structure.

The current method of airport pavement construction is as follows. The influence of groundwater on the asphalt pavement is quantified through laboratory tests and field experiments. Reduction of the design CBR on the subgrade, use of asphalt stabilized material for the base, and installation of a drainage system surrounding the pavement are used to design and construct water-resistant airport pavement. To decrease the subgrade vertical stress, the use of the sandwich type asphalt pavement in which a stiff subbase is laid directly on the subgrade, is being studied. If differential settlement of the ground occurs, concrete pavements will suffer severe damage, in which case reinforced concrete precast slab pavement with a cotter joint system is introduced to repair the damaged slabs. Furthermore, prestressed concrete pavements and the lift-up rehabilitation method are also used for adjusting settled pavements.

The present study on the rough runway profile is conducted as follows. Longitudinal profiles of pavement are measured using a profilometer mounted in a vehicle and combined with the Global Positioning System at normal vehicle speed. The profile data obtained at an airport runway on reclaimed ground are analyzed with conventional spectral analysis and computer simulation of the response of a large aircraft. Finally, the pilots' operation ability and passengers' comfort are analyzed, and then roughness criteria for runways and taxiways are determined. In addition, loading characteristics of moving aircraft and dynamic response of airport pavements to aircraft load are studied.

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