# Strength Requirements in Unsurfaced Soils for Aircraft Operations

## Conditions de force portante des sols non revêtus destinés à la circulation des avions

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**Summary**

This paper describes the development and validation of criteria for determining soil-strength requirements in unsurfaced soils for operation of aircraft.

**Sommaire**

Ce rapport expose la recherche et la vérification des critères auxquels doivent satisfaire les sols pour résister sans revêtement à la circulation des avions.

### Introduction

Criteria for selecting unprepared landing areas capable of supporting a few operations of cargo and assault-type aircraft are urgently needed by engineering officers in theaters of operations. Dimensional criteria for such an airstrip have been proposed by the U.S. Air Force, and soil-strength requirements have been developed by the U.S. Army Engineer Waterways Experiment Station (WES) based on accelerated traffic tests on unsurfaced soils [1]*. The soil-strength requirements have been reasonably well validated by aircraft operations on prepared and unprepared landing strips.

This paper describes the development and validation of the soil-strength criteria.

* Bracketed numbers refer to Bibliography.

### Development of Criteria

*Traffic tests*—Accelerated traffic tests were conducted at WES in connection with a comprehensive program to obtain necessary data for the development of criteria for designing runways surfaced with landing mat and membrane-type materials. Test sections for the landing mat tests were built longer than necessary for the mat tests and portions were left unsurfaced. A number of test sections were constructed, representing subgrades of three different strength ranges : low, medium, and high. The low-strength subgrades were constructed with a fat clay (*CH*) to CBR values of from 3 to 7. The medium-strength subgrades were constructed with the same fat clay but at lower water contents which resulted in CBR values of from 10 to 20. The high-strength subgrades were constructed with a lean clay material to CBR values of above 20. (Fig. 1 shows a test lane in readiness for test.)

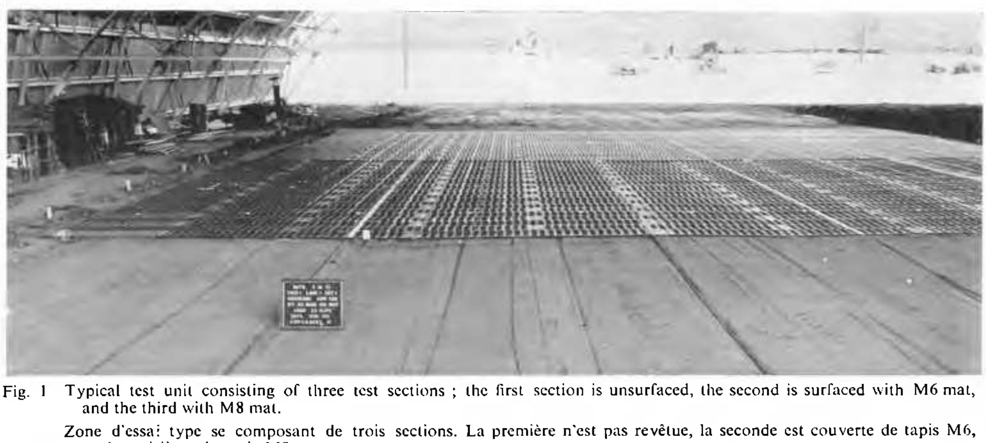

Fig. 1 Typical test unit consisting of three test sections ; the first section is unsurfaced, the second is surfaced with M6 mat, and the third with M8 mat.

Zone d'essai type se composant de trois sections. La première n'est pas revêtue, la seconde est couverte de tapis M6, et la troisième de tapis M8.

Traffic was applied with towed test load carts (Figs. 2 and 3) with single-wheel loads varying from 10,000 to 50,000 lb and tire pressures varying from 40 to 300 psi. A few tests were also made with dual and dual-tandem assembly loads of 50,000 and 100,000 lb, respectively. All traffic was applied by operating the load carts back and forth, shifting laterally on each forward pass to provide uniform coverages over a lane approximately 12 ft wide.


Fig. 2 Self-powered, front-wheel-drive load cart used in tests involving 10,000-lb wheel loads

Véhicule automoteur de mise en charge, à traction avant, employé dans les essais comportant des charges roulantes de 10.000 livres *

* Livre de 453,6 g.

Fig. 3 Load cart used in tests involving wheel loads of 25,000, 50,000, and 100,000 lb. In this view it is loaded to achieve 25,000 lb on a single-wheel assembly.

Véhicule de mise en charge employé dan les essais comportant des charges roulantes de 25.000, 50.000, et 100.000 livres. Dans cette figure la charge atteint 25.000 livres sur une seule roue.

Failure of sections was judged on the basis of deflection under traffic and permanent deformation or rutting. Sections were classed as failed when it was estimated that aircraft operations would be difficult. In general, this involved transient deflections of 0·75 to 1·5 in. and permanent deformations of 2 to 4 in. Fig. 4 shows typical views of sections before failure and after traffic had been continued beyond the failure point.

*Test data and analysis*—It was desired to establish CBR design curves for unsurfaced soils which would indicate the minimum soil-strength requirements for the operation of various types of aircraft for from 1 to 100 coverages. The method of attacking this problem was to use the basic CBR design curves for flexible pavements [2] as a basis and then to determine from the traffic test data the reduction in thickness requirements that could be applied to these basic curves to make them suitable for the less stringent requirements of a temporary unsurfaced or membrane-surfaced landing strip. It should be pointed out that the basic flexible pavement design curves are for all-weather fields, which require that pavements remain waterproof throughout the design life of the field. Also, for this type of construction, the maximum allowable subgrade deflection is about 0·25 in.; whereas, for an unsurfaced subgrade, deflections of as much as 1·5 in. can be tolerated and most cargo planes can operate in ruts up to 4 in. deep. Therefore, the strength requirements for an unsurfaced or membrane-surfaced runway are considerably less than those for a flexible pavement designed to receive the same number of operations.

Data obtained during the traffic test are summarized in table 1. The CBR values shown represent the average strength of about the top 8 in. of subgrade. Fig. 5 presents plots of CBR versus coverages from data given in table 1. The test number is indicated beside each point. The points indicated by "$x$" symbols are from the existing theater-of-operations flexible pavement design curves and represent the minimum base course CBR values needed under surface treatment for the different tire pressures. These were plotted to aid in establishing the slope of the relation between CBR and coverages. This slope was used in extrapolating the results of traffic tests to indicate the CBR required for a range of coverages. For example, to establish CBR requirements for the emergency operational category (40 coverages), the test results from sections that failed at more or less than 40 coverages were extrapolated as follows : Consider test 31 (table 1) in which the CBR of the fat clay was 4, and the test results indicate failure at 10 coverages. Therefore, a point was plotted on Fig. 5b at 10 coverages and a CBR of 4. A line having the same slope as those in the upper part of Fig. 5b was drawn from this point to 40 coverages, intersecting 40 coverages at a CBR of 5. This CBR value was recorded in the table 1 column headed "CBR Indicated as Necessary from Test" opposite "Emergency Category."

The CBR indicated as necessary by the tests was compared with the flexible pavement curves for emergency category (Fig. 6) to determine the indicated reduction in inches from the flexible pavement design curves for this category. For example, for test 31, Fig. 6a indicates that a thickness of 10·3 in. would be required for emergency operation of a 25,000-lb load at 40-psi tire pressure where the subgrade CBR was 5. Since the test indicated that a subgrade CBR of 5 was adequate for 40 coverages, the indicated reduction that can be applied to the basic flexible pavement design curve is 10·3 in. This value is listed in the last column of table 1. This same procedure was used in evaluating the results of each test.

Fig. 7 is a plot of the indicated reduction versus tire pressure for various conditions of tire pressure and load. These data indicate greater reductions with decreasing tire pressure and with increasing wheel load. This is due to the fact that larger tires were used for the low tire pressures and heavier wheel loads and larger deflections were permitted before classing the test section as failed.

The reductions that may be applied to the basic flexible pavement design curves in establishing design curves for unsurfaced landing strips, as indicated by Fig. 7, are tabulated on the following page.

Fig. 4 Typical views of unsurfaced test sections after various coverages of single-wheel load.
Vues types de sections d'essai non revêtues après plusieurs aller et retour de charge.

a. Test 29, after 40 coverages of 10,000-lb load ; failure occurred between 20 and 40 coverages.
Essai No. 29 : après 40 passages aller et retour d'une charge de 10.000 livres ; rupture entre 20 et 40 aller et retour.

b. Test 35, after 2 coverages of 25,000-lb load ; failure occurred at less than 2 coverages.
Essai No. 35 : après 2 passages aller et retour d'une charge de 25.000 livres ; rupture à moins de 4 passages.

c. Test 65, satisfactory after 700 coverages of 25,000-lb load.
Essai No. 65 : satisfaisant après 700 passages aller et retour d'une charge de 25.000 livres.

d. Test 89, satisfactory after 40 coverages of 25,000-lb load ; traffic was resumed and failure occured after about 90 coverages.
Essai No. 89 : satisfaisant après 40 passages aller et retour d'une charge de 25.000 livres. Le trafic fut repris et la rupture s'est produite après approximativement 90 aller et retour.

Table 1
Summary of Traffic Tests on Unsurfaced Soils

| *Test No.* | *Tire Pressure psi* | *Evaluation Data* | | | | | | | | | | | *CBR Indicated as Necessary from Test* | | *Indicated Reduction from Flexible Pavement Design Curves, in.* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Cov* * | CBR | *Cov* * | CBR | *Cov* * | CBR | *Cov* * | CBR | *Cov* * | CBR | *Behavior Under Traffic* | *Operational Category* | CBR | |
| | | | | | | | | | | | | *Single, 10,000-lb Wheel Load* | | | |
| 1 | 40 | 0 | 4 | 40 | 4 | | | | | | | Failure at about 40 cov | Emergency | 4 | 8·0 |
| 20 | 40 | 0 | 14 | 40 | 11 | 170 | 12 | 400 | 11 | 700 | 11 | No distress at 700 cov | Minimum | < 12 | 5·5 |
| 4 | 100 | 0 | 5 | 4 | 4 | | | | | | | Failure between 2 and 4 cov | Emergency | 7·5 | 5·8 |
| 21 | 100 | 0 | 9 | 30 | 8 | 42 | 8 | | | | | Failure between 25 and 30 cov | Emergency | 9·7 | 4·9 |
| 6 | 200 | 0 | 5 | | | | | | | | | Unsatisfactory for traffic | Emergency | > 5 | — |
| 22 | 200 | 0 | 8 | 6 | 7 | | | | | | | Failure at about 2 cov | Emergency | 13 | 4·4 |
| 27 | 200 | 0 | 34 | 40 | 24 | 170 | 31 | 400 | 49 | 700 | 64 | Satisfactory for 700 cov | Minimum | < 44 | 2·2 |
| 29 | 300 | 0 | 23 | 40 | 10 | | | | | | | Failure between 20 and 40 cov | Emergency | 26 | 2·8 |
| | | | | | | | | | | | | Single, *25,000-lb Wheel Load* | | | |
| 31 | 40 | 0 | 4 | 10 | 4 | | | | | | | Failure at about 10 cov | Emergency | 5 | 10.3 |
| 65 | 40 | 0 | 14 | 40 | 16 | 170 | 21 | 400 | 18 | 700 | 12 | Satisfactory for 700 cov | Minimum | < 16 | 6·5 |
| 35 | 100 | 0 | 4 | 2 | 5 | | | | | | | Failure at > 2 cov | Emergency | 7·5 | 9·0 |
| 66 | 100 | 0 | 12 | 40 | 9 | | | | | | | Failure at about 40 cov | Emergency | 12 | 6·5 |
| 70 | 200 | 0 | 12 | 20 | 11 | | | | | | | Failure at about 20 cov | Emergency | 13 | 6·8 |
| 86 | 200 | 0 | 17 | 40 | 25 | 170 | 13 | | | | | Failure between 124 and 170 cov | Emergency | 20.5 | 4·7 |
| 89 | 300 | 0 | 18 | 40 | 20 | 90 | 13 | | | | | Failure between 60 and 90 cov | Emergency | 18·5 | 6·0 |
| | | | | | | | | | | | | *Single, 50,000-lb Wheel Load* | | | |
| 104 | 60 | 0 | 13 | 40 | 11 | 170 | 11 | 400 | 10 | 700 | 14 | Satisfactory for 700 cov | Minimum | < 12 | > 12·0 |
| 106 | 100 | 0 | 12 | 30 | 13 | | | | | | | Failure at 30 cov | Emergency | 13·5 | 8·5 |
| 117 | 100 | 0 | 32 | 40 | 34 | 170 | 40 | 400 | 40 | 700 | 35 | No distress at 700 cov | Minimum | < 42 | 4·0 |
| 118 | 200 | 0 | 28 | 40 | 20 | 70 | 16 | 170 | 14 | | | Failure between 70 and 170 cov | Emergency | 25·5 | 5.0 |
| 120 | 300 | 0 | 29 | 40 | 16 | | | | | | | Failure between 30 and 40 cov | Emergency | 33 | 4.5 |
| | | | | | | | | | | | | *Dual, 50,000-lb Wheel Load* | | | |
| 123 | 100 | 0 | 13 | 40 | 13 | 60 | 7 | | | | | Failure at about 60 cov | Emergency | 12·5 | 6·3 |
| | | | | | | | | | | | | Dual-Tandem, *100,000-lb Wheel Load* | | | |
| 130 | 100 | 0 | 40 | 8 | 76 | 6 | | | | | | Failure at about 76 cov | Emergency | 12 | 6·5 |

* Coverages.

| *Tire Pressure psi* | *Indicated Reduction, in.* | | |
|---|---|---|---|
| | 10,000-lb *Wheel Load* | 25,000-lb *Wheel Load* | 50,000-lb *Wheel Load* |
| 40 | 8·0 | 10·0 | 12·0 |
| 100 | 5·5 | 7·0 | 8·5 |
| 200 | 3·5 | 4·8 | 5·8 |
| 300 | 2·8 | 3·6 | 4·5 |

*Design curves*—CBR design curves for unsurfaced and membrane-surfaced subgrades for the emergency operational category (40 coverages) are shown on Fig. 8. These curves were derived by subtracting the thicknesses as indicated above from the basic flexible pavement design curves shown on Fig. 6. The strength requirements for an unsurfaced or membrane-surfaced subgrade are the same. The benefits gained from use of membrane are primarily waterproofing and dustproofing.

In addition to the CBR design curves for the emergency operational category, criteria for the minimum soil strengths required for an unsurfaced airstrip to support a variable amount of aircraft traffic have been developed. These criteria are shown in the form of CBR versus coverage curves on Figs. 9 and 10, from which the required CBR for any given wheel load and tire pressure can be obtained for any number of coverages from 1 to 100. These latter curves were developed by WES in collaboration with the U. S. Army Engineer Ohio River Division Laboratories (ORDL) and are based on the traffic tests discussed herein and taxi tests conducted by ORDL [3]. The curves for the single-wheel assemblies (Fig. 9) were derived from the curves shown on Fig. 8 by the following procedure. The CBR values indicated on Fig. 8 for the various wheel loads and tire pressures at 0-in. thickness were considered to be the minimum subgrade strengths on which planes could operate successfully for 40 coverages. These values were entered on CBR versus coverage plots similar to those shown on Fig. 5 and were extrapolated to one coverage following the slopes of the solid lines shown in this plot. A family of curves showing the CBR value required for one coverage versus tire pressure for the various wheel loads was then prepared as shown in the left-hand plot of Fig. 9. The slopes in the right-hand plot of Fig. 9 are used in interpolating strength requirements for any number of coverages between 1 and 100. These curves are confirmed by results obtained in studies by both ORDL and WES.

Results of the taxiing tests conducted by ORDL indicated that somewhat higher strengths are required for safe operation of multiple wheels on unsurfaced soils. Therefore, a separate

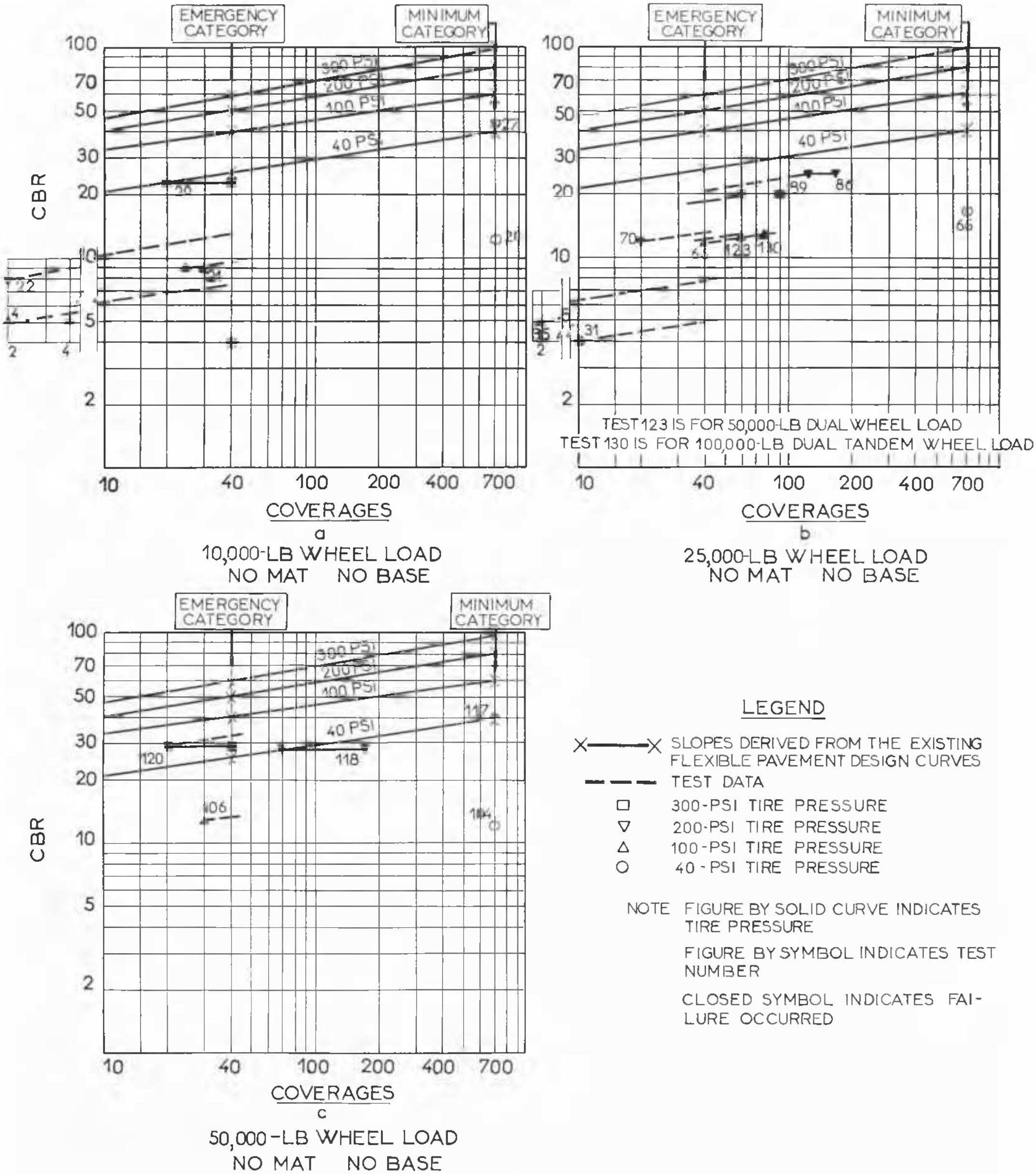


Fig. 5 CBR vs coverages 10,000 lb, 25,000-lb, and 50,000-lb, single-wheel loads. No mat. No base.

CBR en fonction du nombre de passages (aller et retour). Charges par roue de 10.000, 25.000, et 50.000 livres. Pas de tapis. Pas de fondation.

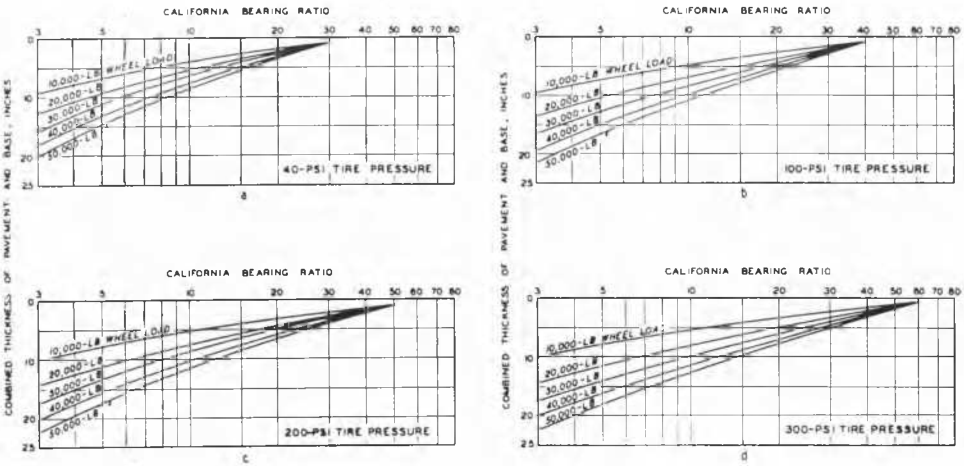


Fig. 6 Theater-of-operations CBR design curves for flexible pavements, emergency operational category.
Graphique CBR pour terrains en zone d'opérations, et diverses pressions de gonflement pour utilisation en cas d'urgence.

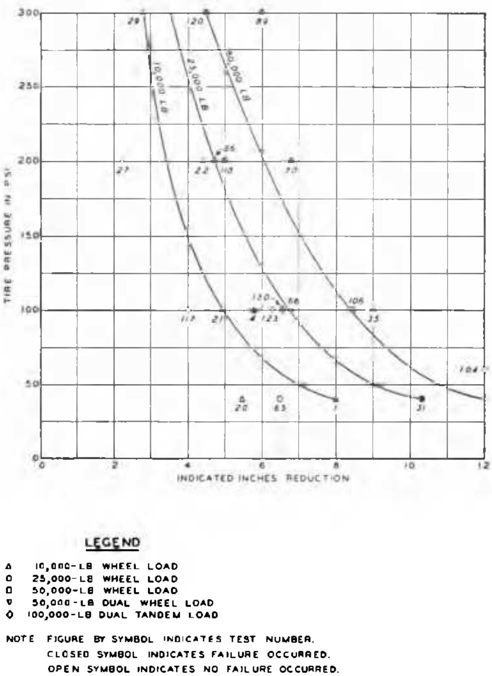


Fig. 7 Tire pressure vs indicated reduction.
Pression de gonflement des pneus en fonction de la réduction d'épaisseur admissible pour les terrains d'opérations par rapport aux terrains permanents.

set of curves (Fig. 10) was prepared for multiple-wheel assemblies. These curves are similar to those shown on Fig. 9, except that the strength requirements are increased by approximately 20 per cent. When the curves for multiple-wheel assemblies are used, the evaluation is based on one wheel of the assembly.

The CBR curves shown on Fig. 8 are applicable for evaluating any subgrade. Sufficient in-place tests should be made to determine that the subgrade strength is equal to or greater than that indicated by the curves at the surface and at the various depths below the surface. The curves shown on Figs. 9 and 10 are applicable where the subgrade strength is fairly uniform or increases with depth.

### Validation of Strength Criteria

Data for validation of strength criteria have been obtained in connection with flight operations on unsurfaced soils with C-122, C-119, C-123B, and C-130A aircraft. The planes are described and tests results are summarized in the following paragraphs.

*Tests with C-122 and C-119 aircraft*—Data on soil-strength requirements for the C-122 (12,000-lb, single-wheel load) and C-119 (27,000-lb, dual-wheel load) aircraft were obtained on a constructed unsurfaced airstrip at Fort Campbell, Ky., in the spring of 1954 [4]. The test strip was constructed by the 18th Airborne Corps in accordance with dimensional criteria recommended by the U.S. Air Force, and soil strengths recommended by WES. The construction consisted of both cut and fill areas. The subgrade soil varied from a fat clay (*CH*) to a lean clay (*CL*) with pockets of silt (*ML*). The desired subgrade strength was a CBR of 7 to 10. The actual strength as constructed was fairly close to the desired strength except in cut areas where slightly lower strength was developed. This was due to remolding of the silty subgrade soil which was quite wet at time of construction. After construction of the test strip and prior to flight operation, a hard surface crust approximately 1 in. thick formed over the subgrade due to drying; this resulted in quite high surface CBR values with decreasing strength with depth.

In flight operations, the planes were landed on the runway and stopped in as short a distance as possible by braking and reversing propellers. The planes were then taxied along an interconnecting taxiway to a parallel taxiway and back to end of runway for a new take-off. Traffic cycles equivalent to about 25 and 40 coverages of the C-122 and C-119 planes, respectively, were made.

Complete subgrade failure did not occur during the traffic; however, the surface crust broke up rapidly and rutting and high deflections occurred in localized areas which were considered failed at the end of flight operations. Soil-strength data were obtained during traffic operations in both satisfactory and failed areas. These data along with the behavior of the subgrade are summarized in table 2.

Table 2

Evaluation of Constructed, Unsurfaced Airstrip

| *Area* | *Sta* | *Behavior* | CBR | | |
|---|---|---|---|---|---|
| | | | *Test Depth* in. | *In-Place Value* | *Required from Design Curve* |
| | | *C-122 Aircraft, 12,000-lb Wheel Load, Tire Pressure 63 psi, 25 Coverages* | | | |
| Runway | 3 + 50 | No distress | 0 | 8 | 7 |
| | | | 6 | 7 | 2·2 |
| | | | 12 | 5 | $<2$ |
| | 16 + 00 | Surface crust broken, 1- to 2-in. deflection under load. Ruts 2 to 4 in. deep | 0 | — | 7 |
| | | | 2 | 4 | 4 |
| | | | 8 | 2 | $<2$ |
| | | | 14 | 7 | — |
| Taxiway | 16 + 50 | Surface crust broken, 1- to 2-in. deflection under load. Ruts 2 to 4 in. deep | 0 | — | 7 |
| | | | 2 | 4 | 4 |
| | | | 6 | 2 | 2·2 |
| | | | 12 | 2 | $<2$ |
| | | | 18 | 7 | — |
| | | *C-119 Aircraft, 13,500-lb Wheel Load, Tire Pressure 78 psi, 40 Coverages* | | | |
| Runway | 25 + 00 | No distress | 0 | 8 | 8 |
| | | | 6 | 9 | 2·3 |
| | | | 13 | 8 | $<2$ |
| | 35 + 50 | Surface crust broken. Rutting started with first pass. At end of 100 cycles ruts 2 to 5 in. deep. (Failed) | 0 | — | 8 |
| | | | 2 | 4 | 4·4 |
| | | | 4 | 2 | 3·0 |
| | | | 10 | 2 | $<2·0$ |
| | | | 14 | 4 | — |
| | | | 20 | 7 | — |
| | 7 + 00 | Surface broken, ruts 2 to 4 in. deep. (Failed) | 0 | 6 | 8 |
| | | | 2·5 | 3 | 4 |
| | | | 6 | 2 | 2·3 |
| | | | 8 | 6 | $<2·0$ |
| | | | 12 | 9 | — |
| | | | 18 | 15 | — |
| Taxiway | 7 + 00 | Started springing between 10 and 14 cycles. Ruts 2 to 3 in. deep at end of 100 cycles. (Failed). | 0 | 4 | 8 |
| | | | 2 | 4 | 4·4 |
| | | | 6 | 3 | 2·3 |
| | | | 10 | 4 | $<2·0$ |
| | | | 14 | 7 | — |
| | 27 + 00 | Slight rutting 1 to 2 in. deep. (Satisfactory) | 0 | 6 | 8 |
| | | | 4 | 6 | 3 |
| | | | 8 | 6 | $<2$ |
| | | | 12 | 9 | — |
| | | | 18 | 16 | — |

Since the subgrade strength decreased with depth, the criteria for soil strength as shown on Fig. 8 should be used for evaluation. Design curves were derived to show the minimum soil-strength requirements for the exact loading and tire pressures of the C-122 and C-119 aircraft for the emergency category. These curves are shown on Fig. 11. The solid-line curves are basic flexible pavement design curves for the emergency operational category. The dashed lines indicate the requirements for unsurfaced soils and were obtained by subtracting 7 in. from the basic curves. The 7-in. reduction was obtained from Fig. 7. The CBR requirements as indicated by the design curves (Fig. 11) corresponding to the various depths shown in table 2 are indicated in the last column of table 2. By comparison of these requirements with the in-place CBR values, it can be noted that no distress occurred where the subgrade strength was equal to or greater than the values indicated by the design curves. However, where the in-place values were less than those indicated by the design curves, failure occurred.

*Tests with C-123B and C-130A aircraft*—Data on soil-strength requirements for the C-123B and C-130A aircraft

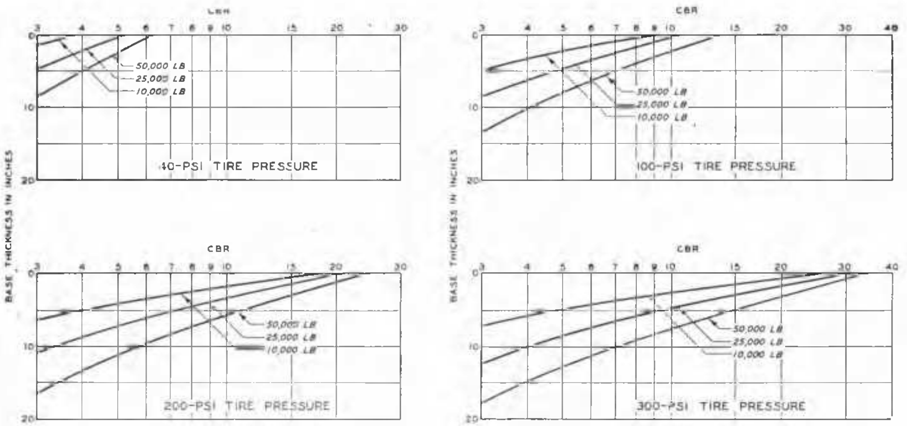


Fig. 8 Theater-of-operations CBR design curves for unsurfaced and membrane-surfaced subgrades, emergency operational category
Graphique CBR pour terrains d'opérations d'urgence, non revêtus, recouverts d'un tapis superficiel.

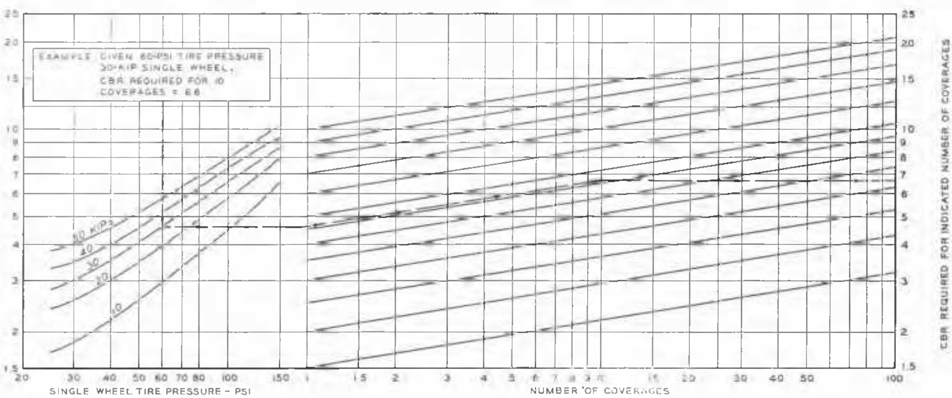


Fig. 9 CBR required for operation of aircraft with single-wheel assemblies on unsurfaced soils.
CBR nécessaire dans le cas d'avions à train d'atterrissage à roues isolées sur sols non revêtus.

were obtained in connection with tests made by the Air Force Operational Test Center, Eglin Air Force Base, Fla., to determine the operational suitability of the aircraft. The C-123B is a high-wing transport aircraft designed to serve as an assault transport capable of operation on rough, unprepared landing strips. The design includes fully reversible propellers and tricycle landing gear. The two main gears are single-wheel assemblies. The C-130A aircraft is similar to the C-123B, except that it is larger, carries a greater gross load, and is equipped with single-tandem main-gear assemblies.

Flight operations were made at two unprepared test sites : one near Eglin Air Force Base, and the other near Pope Air Force Base, North Carolina. Both sites were similar, consisting of a sand subgrade with a thin cover of vegetation. The maximum longitudinal grade was estimated at about 5 per cent. Both areas were quite rough, with bumps and depressions of about 6 to 10 in.

Flight operations consisted of landings, taxiing, maximum-effort stops, turning, and take-offs. The general procedure was for the plane to fly in over a 50-ft obstacle, touch down, and stop in as short a distance as possible, then taxi back to end of runway and take off. Flight operations were made with each plane at a range of wheel loads and tire-inflation pressures.

*Effects on subgrade*—The surface of the sand subgrade deformed and rutted severely during the aircraft operations. The rut depths increased with increase in tire pressure, but were not materially affected by increasing wheel loads at a given tire-inflation pressure. The most severe disturbance to the subgrade occurred during the maximum-effort stops where the brakes were applied and the propellers reversed. Ruts up to 16 in. deep occurred during this type of operation. However, the plane pulled out of the ruts as the brakes were released. Both the C-123B and C-130A aircraft could taxi and take off in ruts up to 4 to 6 in. deep. The C-123B aircraft

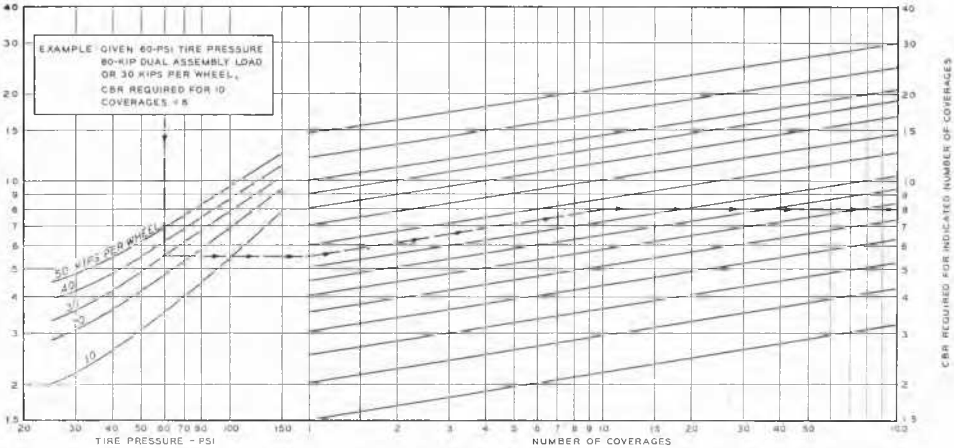


Fig. 10 CBR required for operation of aircraft with multiple-wheel assemblies on unsurfaced soils.
CBR nécessaire dans le cas d'avions à roues jumelées sur des terrains non revêtus.

Table 3
Subgrade Evaluation and Indicated Strength Requirements
C-123B Aircraft

| 1 | 2 | 3 | 4 | 5 | | | | | | | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Main-Gear Tire Pressure psi* | *Type of Operation* | *Aircraft Performance* | *Depth of Rut in.* | *Subgrade Evaluation Average Cone Penetrometer Reading at Indicated Depth, in.* | | | | | | | *Subgrade Rating* | | *Indicated CBR Required* | |
| | | | | 0 | 2 | 4 | 6 | 8 | 10 | 12 | *Cone Index* | *Equivalent CBR* | *From Test* | *From Design Curve* |
| | | | | | | | *Single, 16,200-lb Wheel Load* | | | | | | | |
| 90 | Straight taxi | Borderline | 8 | 7 | 45 | 55 | 70 | 85 | 100 | 115 | 95 | 3·1 | 3·1 | 5·0 |
| 90 | Straight taxi | Immobilized | 13 | 7 | 37 | 53 | 70 | 70 | 70 | 70 | 70 | 2·3 | > 2·3 | |
| 90 | Turning | Immobilized | 16 | 15 | 45 | 61 | 70 | 90 | 105 | 110 | 95 | 3·1 | > 3·1 | |
| 70 | Straight taxi | Satisfactory | 4 | 10 | 30 | 60 | 75 | 85 | 110 | 115 | 95 | 3·1 | 3·1 | 4·0 |
| 70 | Straight taxi | Satisfactory | 2 | 15 | 50 | 80 | 90 | 125 | 130 | 140 | 120 | 4·0 | < 4·0 | |
| | | | | | | | *Single, 18,000-lb Wheel Load* | | | | | | | |
| 41 | Straight taxi | Satisfactory | 1 | 10 | 45 | 70 | 95 | 125 | 155 | 175 | 160 | 5·3 | < 5·3 | 3·0 |
| 41 | Landing touchdown | Tail damage * | 8 | 15 | 35 | 60 | 105 | 115 | 95 | 95 | 105 | 3·5 | — | |
| 41 | Maximum-effort stop | Satisfactory | 8 | 10 | 30 | 55 | 85 | 110 | 140 | 160 | 125 | 4·1 | 4·1 | |
| | | | | | | | *Single, 19,800-lb Wheel Load* | | | | | | | |
| 45 | Straight taxi | Satisfactory | 1 | 10 | 55 | 80 | 130 | 140 | 155 | 155 | 145 | 4·9 | < 4·9 | 3·3 |
| 45 | Straight taxi | Satisfactory | 3 | 10 | 30 | 50 | 85 | 115 | 135 | 140 | 120 | 4·0 | < 4.0 | |
| | | | | | | | *Single, 21,000-lb Wheel Load* | | | | | | | |
| 49 | Straight taxi | Satisfactory | 1 | 15 | 60 | 75 | 100 | 120 | 155 | 155 | 135 | 4·5 | < 4·5 | 3·6 |
| 49 | Reversed propellers | Satisfactory | 2 | 8 | 38 | 65 | 80 | 110 | 135 | 160 | 120 | 4·0 | < 4·0 | |
| 49 | Maximum-effort stop | Left tire locked causing skidding | 15 | 10 | 32 | 48 | 60 | 80 | 90 | 110 | 84 | 2·8 | 2·8 | |

Note : Cone penetrometer readings shown under column 5 are averages of several readings obtained adjacent to the indicated rut.
The cone index value shown under column 6 is the numerical average of the cone penetrometer reading for the 6-, 8-, 10-, and 12-in. depths.
* Unusually hard landing caused slight tail damage to aircraft.

was immobilized during taxiing with main-gear tires inflated to 90 psi. The immobilization occurred in ruts 13 to 16 in. deep. No take-offs or landings were attempted at the 90-psi tire pressure. All landings and take-offs were accomplished at tire pressures of 70 psi and less.

*Strength evaluation*—During the tests with the C-123B aircraft, subgrade strength measurements were made with a cone penetrometer having a 30-deg. cone of 1/2-sq.-in. base area. During the tests with the C-130A aircraft, strength measurements were made with a similar instrument, called

Table 4
Subgrade Evaluation and Indicated Strength Requirements
C-130A Aircraft

| 1<br>Aircraft Loading, lb<br>Gross | 2<br>Single Tandem Main-Gear Assembly | 3<br>One Main-Gear Wheel | 4<br>Type of Operation | 5<br>Aircraft Performance | 6<br>Depth of Rut in. | 7<br>Subgrade Evaluation<br>Average Airfield Penetrometer Reading at Indicated Depth, in.<br>0 | 2 | 4 | 6 | 8 | 10 | 12 | 8<br>Subgrade Rating<br>Soil Index | 9<br>Equivalent CBR | 10<br>Indicated CBR Required<br>From Test | 11<br>From Design Curve |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Main-Gear Tire Pressure, 60 psi* | | | | | | | | | | | | |
| 80,000 | 36,000 | 18,000 | Straight taxi | Satisfactory | 4 | 0·0 | 1·7 | 4·7 | 7·0 | 8·3 | 9·0 | 9·0 | 8·3 | 7·4 | | 5·0 |
| | | | | | 3 | 0·2 | 1·8 | 3·0 | 4·4 | 5·4 | 6·0 | 6·8 | 5·6 | 4·7 | 4·7 | |
| | | | | | 2 | 0·1 | 1·7 | 2·9 | 4·2 | 5·6 | 6·7 | 7·0 | 5·9 | 5·0 | | |
| | | | | | 1 | 1·0 | 3·0 | 4·5 | 6·0 | 7·0 | 7·4 | 7·6 | 7·0 | 6·0 | | |
| 80,000 | 36,000 | 18,000 | Turning | Satisfactory | 7 | 0·5 | 0·9 | 1·3 | 1·9 | 2·5 | 2·9 | 4·0 | 2.8 | 2·1 | | |
| | | | | | 5 | 0·0 | 1·5 | 2·5 | 3·1 | 3·8 | 4·3 | 4·4 | 3·9 | 3·1 | | 5·0 |
| | | | | | 3 | 0·5 | 1·6 | 2·9 | 3·9 | 4·8 | 5·3 | 6·0 | 5·0 | 4·1 | | |
| | | | | | 1 | 0·7 | 3·0 | 4·7 | 6·5 | 8·0 | 9·5 | 10·0 | 8·5 | 7·6 | | |
| 80,000 | 36,000 | 18,000 | Maximum-effort stop | Satisfactory | 16 | 0·0 | 1·0 | 1·7 | 2·3 | 3·0 | 3·3 | 4·0 | 3·2 | 2·4 | > 2·4 | 5·0 |
| | | | | | 8 | 0·5 | 2·2 | 2·9 | 3·8 | 5·6 | 5·8 | 6·1 | 5·4 | 4·5 | | |
| 90,000 | 40,500 | 20,250 | Straight taxi | Satisfactory | 5 | 0·5 | 1·1 | 2·0 | 2·7 | 3·9 | 4·5 | 5·8 | 4·2 | 3·4 | 3·4 | 5·1 |
| | | | | | 4 | 0·9 | 2·4 | 3·4 | 4·6 | 5·6 | 6·0 | 5·8 | 5·3 | 4·4 | | |
| | | | | | 2 | 1·5 | 2·5 | 3·3 | 4·3 | 6·0 | 7·0 | 7·0 | 6·1 | 5·2 | | |
| | | | | | 1 | 1·0 | 3·3 | 5·0 | 6·5 | 9·5 | 8·4 | 8·4 | 8·2 | 7·3 | | |
| 90,000 | 40,500 | 20,250 | Turning | Satisfactory | 4 | 0·6 | 1·5 | 2·3 | 3·4 | 3·9 | 4·3 | 4·9 | 4·1 | 3·3 | 3·3 | 5·1 |
| | | | | | 3 | 0·8 | 1·8 | 2·8 | 3·7 | 4·8 | 5·2 | 5·6 | 4·8 | 4·0 | | |
| | | | | | 2 | 0·7 | 2·3 | 3·4 | 4·5 | 5·3 | 6·0 | 6·5 | 5·6 | 4·7 | | |
| | | | | | 1 | 1·0 | 3·0 | 4·2 | 5·5 | 6·7 | 7·3 | 8·0 | 6·9 | 6·0 | | |
| 90,000 | 40,500 | 20,250 | Maximum-effort stop | Satisfactory | 10 | 1·0 | 2·0 | 3·0 | 3·8 | 4·3 | 4·3 | 4·8 | 4·3 | 3·5 | 3·5 | 5·1 |
| | | | | | 8 | 0·8 | 2·4 | 3·2 | 3·7 | 4·3 | 5·0 | 6·0 | 4·8 | 4·0 | | |
| 96,000 | 43,250 | 21,625 | Straight taxi | Satisfactory | 5 | 0·1 | 1·0 | 1·9 | 2·5 | 3·3 | 4·1 | 4·4 | 3·6 | 2·8 | 2·8 | 5·3 |
| | | | | | 1 | 1·0 | 3·8 | 4·8 | 5·9 | 7·8 | 8·9 | 9·8 | 8·1 | 7·2 | | |
| 96,000 | 43,250 | 21,625 | Turning | Satisfactory | 4 | 0·9 | 2·6 | 3·6 | 5·0 | 5·9 | 6·5 | 7·1 | 6·1 | 5·3 | < 5·3 | 5·3 |
| | | | | | 1 | 2·0 | 5·5 | 7·6 | 10·5 | 10·9 | 11·5 | 11·3 | 11·0 | 10.0 | | |
| 102,000 | 46,000 | 23,000 | Straight taxi | Satisfactory | 3 | 0·1 | 1·4 | 2·4 | 3·9 | 5·1 | 6·4 | 7·5 | 5·6 | 4·7 | < 4·7 | 5·5 |
| | | | | | 1 | 2·1 | 4·0 | 7·5 | 9·9 | 11·8 | 12·0 | 12·0 | 11·4 | 10·4 | | |
| | | | | *Main-Gear Tire Pressure, 55 psi* | | | | | | | | | | | | |
| 100,000-116,000 | 57,200 | 26,000 | Straight taxi | Satisfactory | 2-1/2 | 0·5 | 1·3 | 2·4 | 4·1 | 5·8 | 7·3 | 8·0 | 6·3 | 5·4 | < 5·4 | 5·4 |
| | | | | | 1 | 0·6 | 2·1 | 4·3 | 7·2 | 9·2 | 10·3 | 10·5 | 9·3 | 8·3 | | |
| | | | | | 1/2 | 0·5 | 3·9 | 7·4 | 10·2 | 14·0 | 14·0 | 14·0 | 13·0 | 12·0 | | |
| 100,000-116,000 | 57,200 | 26,000 | Turning | Satisfactory | 3 | 0·9 | 4·1 | 6·6 | 8·2 | 10·8 | 11·5 | 12·0 | 10·6 | 9·6 | < 9·6 | 5·4 |
| | | | | | 2 | 0·8 | 2·9 | 5·3 | 8·0 | 10·3 | 13·2 | 14·5 | 11·5 | 10·5 | | |
| 100,000-116,000 | 57,200 | 26,000 | Maximum-effort stop | Satisfactory | 11 | 0·5 | 2·1 | 3·7 | 6·3 | 8·3 | 9·7 | 10·0 | 8·6 | 7·7 | | 5·4 |
| | | | | | 6 | 1·3 | 2·2 | 4·0 | 5·8 | 7·7 | 9·0 | 10·0 | 8·1 | 7·2 | < 7·2 | |

Note : Airfield penetrometer readings shown under column 7 are averages of several readings obtained adjacent to the indicated rut.
The soil index value shown under column 8 is the numerical average of the penetrometer readings at the 6-, 8-, 10-, and 12-in. depths.

an airfield penetrometer, which has a 30-deg. cone with a base diameter of 1/2 in. (area 0·196 sq. in.). Sufficient in-place CBR determinations were made along with the penetrometer readings to obtain a correlation between penetrometer reading and CBR. The strength measured with the penetrometers was converted to CBR for comparison with design requirements. The data collected during the tests with the C-123B aircraft are summarized in table 3. The cone penetrometer readings shown in column 5 were obtained at various increments of depth in undisturbed soil adjacent to the ruts made by the aircraft and are assumed to represent the subgrade strength where the rut occurred. The readings were very low at the surface, but increased rapidly to a depth of 6 to 8 in. with a tendency to level off below 8 in. The low surface strength was due to a loose surface condition of the sand resulting from the lack of confinement and was a factor influencing the depth of rutting. However, the pilots experienced no difficulties in operating the planes in ruts up to 4 to 6 in. deep. Therefore, for the sand subgrades, the strength between the 6 and 12-in. depth appeared to be the controlling factor in the over-all successful operation of the aircraft. The arithmetic average of the penetrometer readings for the 6-, 8-, 10-, and 12-in. depths was used in rating the subgrade; these ratings are shown in columns 6 and 7 of table 3.

*Strength requirements*—The indicated CBR required for satisfactory operation of the C-123B aircraft is shown in columns 8 and 9 of table 3. The values in column 8 are based on the subgrade rating (column 7) and the aircraft performance (column 3). For example, refer to line 1 of table 3. A straight taxiing operation with a 16,200-lb, single-wheel load, 90-psi tire pressure, on a subgrade with a CBR of 3·1 resulted in a rut 8 in. deep. The aircraft was able to continue moving through the 8-in. rut, but was immobilized in a 13-in. rut (line 2) where the subgrade CBR required for

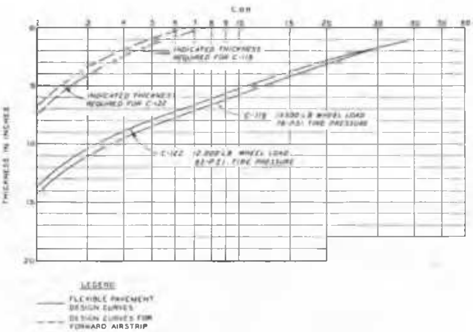

Fig. 11 Curves derived from theater-of-operations flexible pavement design curves, emergency category, single wheels.

Graphique CBR comparé dans le cas normal et celui des terrains en zone d'opérations d'urgence, cas des zones isolées.

taxiing of the aircraft is greater than 2·3 and about equal to 3·1. However, while the aircraft was turning in an area where the subgrade CBR was 3·1, it was immobilized in a 16-in. rut. Therefore, for over-all successful operation of the aircraft with a 16,200-lb wheel load and 90-psi tire pressure, a CBR greater than 3·1 is required. For the taxi test with 70-psi tire pressure, a rut 4 in. deep was made in the subgrade with a CBR of 3·1. The plane was successfully operated for a number of landings and take-offs where ruts of this magnitude were made during taxiing. Therefore, a CBR of 3·1 is considered adequate. For tire pressures of less than 70 psi, the in-place strength was more than adequate for the aircraft operations.

The relatively deep ruts indicated during landing operations did not affect the operation of the aircraft, as the wheels climbed out of the ruts as soon as brakes were released. The CBR values listed in column 9, table 3, were obtained from Fig. 9 which show the design criteria for soil strength for operation of aircraft with single-wheel assemblies on unsurfaced soils. The values listed are the indicated CBR requirements for one coverage.

Similar data obtained during operation of the C-130A aircraft are shown in table 4. The indicated CBR's required, listed in column 11 of table 4, were obtained from Fig. 10 which indicates the CBR requirements for operation of aircraft with multiple-wheel assemblies. From both tables 3 and 4, it can be seen that the indicated CBR required by the design criteria is in fair agreement with the values indicated as being required by the test.

## Conclusions

The soil-strength requirements for operation of aircraft on unsurfaced soils, as shown on Figs. 8, 9, and 10, have been reasonably well validated and can be used with confidence in selecting unprepared landing areas.

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