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# DESIGN PROCEDURE FOR ESTABLISHING AIRCRAFT CAPABILITY TO OPERATE ON SOIL SURFACES

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

# NOTICE

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AFFDL-TR-72-129

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## FOREWORD

This report was prepared by the Aerospace Mechanics Group of the University of Dayton Research Institute under USAF Contract F33615-70-C-1170. The work was conducted under the direction of the Vehicle Equipment Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, Mr. George J. Sperry (FEM), Project Engineer.

The authors wish to thank both Mr. Sperry and Capt. William Lamb, ASD/XRL, for their specific input in relation to the M/STOL aircraft and their review comments of the initial design procedure. This report was submitted by the authors in September 1972.

Publication of this report does not constitute Air Force approval of the reported findings or conclusions. It is published only for the exchange and stimulation of ideas.

K. H. Digges
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Chief, Mechanical Branch
Vehicle Equipment Division
Air Force Flight Dynamics Laboratory

## ABSTRACT

This report summarizes a systematic design procedure for establishing various landing gear combinations of tire sizes, spacings, and configurations which will minimize rolling drag and satisfy the criteria of 200 nonbraking passes of a selected STOL aircraft operating on a standardized CBR6 (or equivalent) soil surface. The design procedure presented herein combined the latest results of Air Force sponsored landing gear/soil interaction research with the previously developed WES coverage techniques.

This procedure is a first attempt to make the research results of existing Air Force Flight Dynamics Laboratory programs available toward the improvement of flotation design capability. This design procedure, subject to certain stated limitations, includes techniques for (1) predicting rolling and braking drags and drag ratios, (2) incorporating multiwheel influences on drag and sinkage, and (3) determining aircraft passes. Additionally, the design procedure has been incorporated in a computer program format for utilization on the CDC 6600 located at Wright-Patterson Air Force Base. The computer program is restricted at present to aircraft with tricycle type landing gear systems.

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## LIST OF SYMBOLS

| | |
|---|---|
| $A$ | Tire Contact Area (Rigid Surface) |
| A/C | Aircraft |
| $A_M$ | Single Tire Contact Area of Main Tires |
| $A_N$ | Single Tire Contact Area of Nose Tires |
| $AP_M$ | Aircraft Passes of Main Gear |
| $AP_N$ | Aircraft Passes of Nose Gear |
| $B$ | Outer Tire to Outer Tire Twin Type Spacing Within a Main Gear (see Figure 3) |
| $b$ | Tire Section Width |
| $C$ | Coverages |
| CBR | California Bearing Ratio |
| CG | Center of Gravity |
| CI | Cone Index |
| $D$ | Tire Outside Diameter |
| $D'$ | Centerline Spacing Between Nose Gear Tires |
| $D_F$ | Rim Flange Diameter |
| $d$ | Tire Deflection in Inches |
| $E$ | Center of Gravity to Center of Gravity Spacing Between Main Gears |
| ESWL | Equivalent Single Wheel Load |
| $F$ | Spacing Between Center of Gravity of Nose Gear and Center of Gravity of Main Gear |
| GW | A/C Gross Weight |
| $J$ | Distance from Ground Line to Center of Gravity of Aircraft |
| $K_m$ | Drag Modifier for Tandem Wheel Tracking Situations |
| $K_n$ | Drag Modifier for Twin Wheel Tracking Situations |
| $\ell$ | Tire Footpring Length (Rigid Surface) |
| $L$ | Distance from Center of Gravity of Nose Gear System to Forward Center of Gravity of Aircraft |
| $L'$ | Distance from Center of Gravity of Nose Gear System to Aft Center of Gravity of Aircraft |
| $M$ | Distance from Center of Gravity of Main Gear System to Aft Center of Gravity of Aircraft |

## LIST OF SYMBOLS (Continued)

| | |
|---|---|
| $M_M$ | Multiple Wheel Drag Modifier |
| $m$ | Tandem-Tracking Tire Spacing Factor |
| $N$ | Number of Tires per Landing Gear |
| $N_M$ | Number of Tires per Main Gear Bogie |
| $N'_M$ | Number of Main Tires on A/C |
| $N_N$ | Number of Nose Tires on A/C |
| $N_m$ | Number of Wheels in a Tandem-Tracking Situation |
| $N_n$ | Number of Wheels in a Twin Situation |
| $n$ | Twin-Tire Spacing Factor |
| $P$ | Vertical Load |
| $P_a$ | Passes |
| $P_M$ | Allowable Passes for the Main Gear |
| $P_N$ | Allowable Passes for the Nose Gear |
| $F/A$ | Contact Pressure |
| $P_a/C$ | Passes per Coverage |
| $R$ | Rolling Drag Resistance to Forward Motion |
| $R_B$ | Braked Tire Drag Force |
| $R/P$ | Rolling Drag Ratio |
| $R_B/P$ | Braking Drag Ratio |
| $(R/P)_s$ | Single Wheel Drag Ratio |
| $(R/P)_M$ | Multiple Wheel Drag Ratio |
| $r$ | Tire Contact Radius |
| $r'$ | Tandem-Nontracking Spacing Factor |
| $S$ | Percent Slip for Braked Tire |
| $S_m$ | Tire Spacing, ℄ to ℄ of Wheel Centers in Tandem Arrangements |
| $S_n$ | Tire Spacing, ℄ to ℄ of Twin Tires |
| STOL | Short Takeoff and Landing Type Aircraft |
| SWL | Single Wheel Load |
| TSMGL | Total Static Main Gear Load |

## LIST OF SYMBOLS (Continued)

| | |
|---|---|
| TSNGL | Total Static Nose Gear Load |
| $W_M$ | Width of Tire Contact Area, $.874\sqrt{A_M}$ for Main Gear Tire |
| $W_N$ | Width of Tire Contact Area, $.874\sqrt{A_N}$ for Nose Gear Tire |
| X | Parameter Determined in Aircraft Passes Procedure (see Figure 9) |
| Y | Parameter Determined in Aircraft Passes Procedure (see Figure 9) |
| Z | Instantaneous Tire Sinkage |
| $(Z/D)$ | Sinkage Ratio |
| $Z/\ell$ | Sinkage Characteristic |
| $\delta$ | Percent Deflection |

## SECTION I

## SUMMARY (LIMITATIONS/FUTURE REQUIREMENTS)

The design procedure provided in this report represents a significant step forward in the development of tools needed by the planner and designer to optimize aircraft capability to operate on soil surfaces. This procedure was specifically developed for aircraft having takeoff/landing weights of 150,000 to 250,000 lbs and low horizontal speeds (close to or less than 40 knots). Comparison/prediction capability has been limited to operation on a cohesive type soil in an unsaturated condition having a strength rating of CBR6 or equivalent.

For the first time, a systematic technique is made available to predict/compare the capability of various possible landing gear configurations in terms of first pass rolling and braked drag, drag ratio, and tire sinkage. Use of the technique provides a logical basis for the selection of the best landing design for a specific aircraft to meet its mission requirements, bearing in mind that applicable trade-offs must be made with other aircraft landing gear design constraints. A new insight is provided concerning the effects of braking on soil in terms of drag (strut) loads experienced and excessive runway damage caused. Maximum braking drag on soil is obtained under fully locked wheel conditions, whereas on rigid surfaces it is achieved at approximately 30% wheel slip. Fully locked wheel braking on soil can result in drag loads and tire sinkages three to eleven times higher than under free rolling conditions, without considering additional drag induced by side loads due to wind and steering. In fact, one locked wheel pass over a low strength soil, particularly sands, can result in rut depths in excess of the current criteria for surface failure, whereas under free rolling and minimum braking conditions, many passes would be required over the same soil surface to reach the limiting rut depth associated with failure. A knowledge of these factors and the results of applying the procedures contained in this report provide a means to improve braking system design as well as aircraft pilot instructions for on-soil operation.

Previously developed Army Corps of Engineers Waterways Experiment Station (WES) criteria is contained in this report as a logical means to compare the flotation capability of various landing gear. It must be emphasized that the WES techniques provide only a rough indication of the number of rolling aircraft passes which can be made under real life conditions prior to the point that a specific degree of runway surface failure is exhibited. Many existing aircraft can effectively operate on runway surfaces which have a significantly higher degree of damage.

Adequate criteria does not exist to enable the planner, designer, or the operating command to properly accomplish their functions related to aircraft operation on soil. The planner requires capability to relate mission requirements to real life conditions and a sound basis for making necessary trade offs. Design criteria is needed to insure that required component capability and strength is provided to achieve established requirements for aircraft surface handling characteristics and flotation with minimum fatigue damage to the aircraft. The aircraft operator must be provided realistic aircraft surface handling characteristics/limitations and procedures for effective operation on soil; a real time means to determine airfield properties related to aircraft characteristics; and a fast, reliable means to establish specific aircraft capability to operate at a specific existing soil surfaced airfield.

A significant amount of active, coordinated work must be done by the aircraft and civil engineering communities to develop the minimum criteria required. For all modes of aircraft operation on soil and their major variables, methods must be developed to establish the forces resulting at the landing gear/soil interface and resulting soil surface damage. In addition, the dynamic interface forces must be related to the operation and fatigue characteristics of the critically affected aircraft components. To date (1972) an extensive amount of work has been done related to slow speed, straight rolling conditions, and some work has been done concerning straight roll and braking in the 5 to 40 knot speed range. Limited knowledge is available for operation modes at speeds above 40 knots. The majority of work to date has been under essentially steady state conditions. Only a very limited amount of work has been done related to steering, turning, point of impact, and point of rotation modes of operation; and to establish "roll out" forces resulting from tire sinkage due to extended parking on soil, engine run-up, and load/off load operations. Additionally, a means must be developed to consider the various types, designs, and mechanical properties of aircraft tires in terms of their performance on soil since existing work has been restricted to the standard bias tire size, inflation pressure, and flat surface deflection relationships. The major constitutive strength properties of soil related to tire soil interaction have not been fully established. Current methods such as CBR, California Bearing Ratio, and Cone Index do not enable reliable or accurate prediction of tire/soil interface forces and resulting surface damage. Simple, rapid techniques are needed to establish soil surface strength, roughness, and texture properties which can be related to various aircraft surface operating modes.

This report, which is an initial step, represents a significant improvement in the criteria available for determining aircraft/ground design and operational characteristics. Further improvements in the criteria will require the full energy and cooperation of the aircraft and civil engineering communities if fully adequate criteria is to be developed.

# SECTION II

# INTRODUCTION

This report presents a standardized procedure for incorporating maximum surface flotation capability into the landing gear system for a proposed Medium STOL aircraft which includes in its mission the capability to operate on unsurfaced (soil) runways. The ability of the aircraft to operate on soil runways is defined as flotation. The basic design criteria used in the following flotation analysis procedure is the minimization of rolling tire horizontal drag loads in the takeoff mode while insuring the required minimum number of aircraft nonbraked passes using the WES coverage technique. This minimization of drag is an important consideration with reference to takeoff length, thrust, and lift requirements. Additionally, a technique is given to determine the horizontal braked drag forces for braked tire operation on soil. Each of the above factors can be assigned a weighting factor to develop its contribution towards the final landing gear candidate selection. Note that this procedure is not a complete landing gear design approach, but rather just that part which predicts the tire/soil interaction drag and sinkage in the rolling and braking mode and runway coverages. The designer must devise his own techniques for the selection of suitable weighting factors applied to the information given here and to the added information that he has available concerning landing gear weight, gear position, wind drag, etc., leading to a final landing gear design satisfying USAF requirements. Note that this procedure permits the optimization of the flotation characteristics of the landing gear contact elements but does not supercede the load factor procedure currently specified in Mil Spec AFSC DH2-1, used for designing the structural requirements of the landing gear. The above procedure is subject to the limitations described in Section I.

## Glossary of Flotation/Operation Terminology

This analysis procedure is derived from research done by the University of Dayton Research Institute(1,2,3,4) and from methods published by the USAF(5, 6).

The following glossary is intended to familiarize the designer with the current flotation terminology.

Braking Drag Ratio ($R_B/P$) - The braking drag ratio is numerically equal to the longitudinal load on a braked aircraft tire (or landing gear) divided by the vertical load (or landing gear vertical load). The longitudinal load is referred to as the braked drag load ($R_B$) and the vertical load as P.

California Bearing Ratio (CBR) - A measure of the bearing capacity of soil. The CBR is expressed in comparative terms as a percentage of the bearing capacity of a given soil to that of a standard crushed limestone surface. Details of the test procedures used to determine the CBR value of a soil are contained in Mil-Std-621.

Cone Penetration Test (CI) - The cone penetration test is performed with a mobility cone penetrometer. This test measures the resistance to penetration profile of a soil by measuring the load necessary to force a rod equipped with a cone tip into the surface to a given depth. The Cone Index, CI, value is then computed as the average force necessary for penetration to a certain depth (usually 6") divided by the cone top's cross section area (0.5 sq. in. for the Mobility Cone). See TM5-530 or AFM 88-51.

Coverages - One coverage is equal to the number of passes of a given tire or aircraft (group of tires) to completely cover the given width of airfield once.

| | |
|---|---|
| Equivalent Single Wheel Load (ESWL) | The theoretical load which, if acting on a single tire and with a contact area equal to that of one tire of the assembly, will produce the same runway deterioration effect on the airfield as the multiple wheel assembly. |
| Flotation | Flotation is a term used to describe the overall capability of an aircraft to operate on a soil runway. Flotation includes the consideration of such items as: type of surface, mode of operation (taxie, takeoff, landing), turning, etc. |
| Multiple Wheel Drag Modifier ($M_M$) | The $M_M$ value is a number, calculated from semi-empirical relationships, that describes the effect upon the rolling drag ratio (R/P) of a single tire caused by adjacent tires. |
| Rolling Drag (R) | The longitudinal force experienced by a rolling tire (or landing gear) is called rolling drag. |
| Rolling Drag Ratio (R/P) | The rolling drag ratio is a dimensionless quantity equal to the rolling drag load divided by the tire vertical load at any instant. It can also be used to express the average drag ratio for an aircraft by dividing the total drag force on the aircraft by the gross weight transmitted to the ground by the landing gear system. |
| Sinkage Ratio (Z/D) | The sinkage ratio is equal to the instantaneous sinkage of the tire into the soil divided by the unloaded tire diameter. |

| | |
|---|---|
| Slip | - Slip defines the degree of braking. Zero percent slip represents a rolling wheel and 100% slip represents a locked wheel. |
| Tandem Tires | - Tandem tires are two or more tires that are not operating about the same theoretical wheel axis. Tandem tracking tires are two or more tires that operate in the same longitudinal centerline. Tandem nontracking tires are neither operating in the same longitudinal centerline or about the same wheel axis. |
| Tire Load | - The tire load is considered that portion of the aircraft gross weight transmitted through any given tire at any instant to the ground. |
| Twin Tires | - Twin tires are two or more tires that operate about the same theoretical wheel axis. |

# SECTION III

# DESIGN PROCEDURE

This section presents the standardized design procedure for the purpose of optimizing the flotation capability of a landing gear. In particular, the analysis procedures have been developed for a 150,000 to 250,000 lb STOL aircraft with the requirements of a minimum of 200 passes on a CBR6 (or equivalent) soil.

The general procedure for optimizing the flotation capability of landing gears consists of a series of calculations which must be performed for each of the selected tires and landing gear systems (group of tires). The result will be a number of tire/landing gear systems to which appropriate weighting factors can be assigned for:

- minimization of rolling drag
- maximization of passes
- maximization of braking drag.

Additional weighting factors must be assigned to such considerations as gear weight, surface area of gear, storage volume requirements, etc., leading to the final selection of the tire/landing gear system which is most appropriate for the aircraft.

The Gross Weight (GW) of the aircraft used to determine the Total Static Main Gear Load (TSMGL) or Total Static Nose Gear Load (TSNGL) is the static gross weight for the aircraft operating on soil runways. This design static gross weight for operations on soil runways may be less than the design static gross weight for aircraft operations on paved runways. In determining rolling and braked tire drags, the vertical load, P, given in the equations should be taken to $SWL_M$ or $SWL_N$ depending on whether the calculation is being made for a main gear wheel or nose gear wheel respectively.

## Computation of Aircraft Rolling Drag Ratio, R/P

1. Select a group of candidate tires which encompass a range of tire diameters (D) and allowable tire gross loads. Each different tire will be

loaded only to its rated static load as given by Mil-T-5041. Therefore, the total number of tires in the main gear, for example, can be calculated as the total gear load divided by the rated static load for the tires used on that gear (see Figure 1).

2. For each of the selected tires (main and nose), calculate the following parameters using a percent tire deflection, $\delta$, for which the tire will operate on a soil runway (this percent tire deflection is normally larger for soil operations than for hard surface operations).

a. Tire Footprint Length, $\ell$

Tire manufacturer test data on flat surface footprint length, $\ell$, should be used whenever possible due to tire variations. For tire types other than the current standard bias tires, manufacturers data for footprint length should be used.

$d = \dfrac{\delta(D - D_F)}{200}$ = tire deflection (units of length)

$D$ = Tire Diameter

$D_F$ = Rim Flange Diameter

b. Tire Contact Area, A

Tire manufacturer test data for a specific tire which establishes the tire flat surface contact area, A, should be used whenever possible due to tire variations. For tire types other than current standard bias tires, manufacturers data for the contact area must be used.

c. Tire Contact Radius, r

$$r = \sqrt{\frac{A}{\pi}}$$

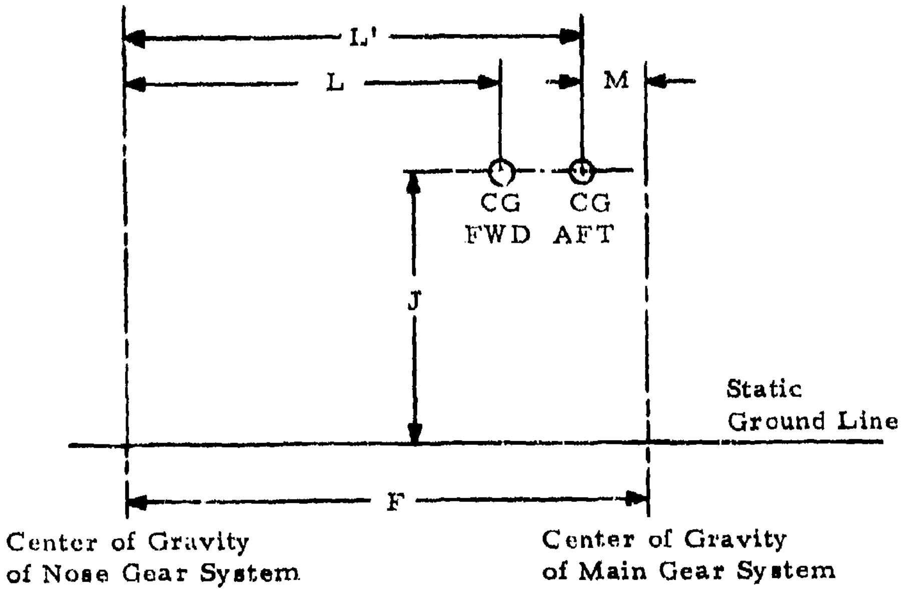
d. Single Wheel Load, SWL

(see Figure 1)

e. Rigid Surface Contact Pressure, P/A

$$P/A = \frac{P}{\text{tire contact area}}$$

$P = SWL$



1. Main Gear

Total Static Main Gear Load (TSMGL) $= \dfrac{GW \times (F-M)}{F}$

Single Wheel Load $= SWL_M = \dfrac{(TSMGL)}{N'_M} = \dfrac{GW \times (F-M)}{F \times N'_M}$

2. Nose Gear

Total Static Nose Gear Load (TSNGL) $= \dfrac{GW \times (F-L)}{F}$

a. SWL for Rolling Drag Calculation

Single Wheel Load $= SWL_N = \dfrac{(TSNGL)}{N_N} = \dfrac{GW \times (F-L)}{F \times N_N}$

b. SWL for Operations Calculation (deceleration rate assumed to be 10 ft/sec$^2$)

Single Wheel Load $= SWL_N = \dfrac{GW \times (F-L)}{F \times N_N} + \dfrac{10 \times GW \times J}{32.2 \times F \times N_N}$

where:

GW = Aircraft Gross Weight

$N'_M$ = Number of Main Tires on A/C

$N_N$ = Number of Nose Tires on A/C

Figure 1. Aircraft Weight Distribution

### Based on a CBR6 (or equivalent) Soil

f. Sinkage Characteristic, $\frac{Z}{\ell}$

$Z$ = Sinkage

$\frac{Z}{\ell} = f(P/A)$, determine from Figure 2

g. Sinkage Ratio, $\frac{Z}{D}$

$$\frac{Z}{D} = \frac{Z}{\ell} \cdot \ell \cdot \frac{1}{D}$$

h. Horizontal Single Wheel Rolling Drag Ratio, $(R/P)_s$

$(R/P)_s = f(Z/D)$, determine from Figure 3

This last parameter $(R/P)_s$ is the rolling single wheel ratio of the horizontal soil drag force (R) to the vertical load on the tire (P) for the CBR6 (or equivalent) soil. The smaller the value of $(R/P)_s$, the better the flotation capacity of the aircraft when operating on soil runways (less drag, shorter takeoff lengths). It has also been shown that minimizing rolling drag results in maximizing aircraft passes on soil runways.

3. Arrange each size tire into reasonable configurations for landing gear bogie. Several configurations of each size tire may be possible. When initially setting the tire spacings, follow the spacing guidelines shown in Figure 4. Due to the use of a CBR6 strength soil, Figure 4 was developed from experimental data in the low sinkage range (less than 1/2" to 3/4"). Note that tandem-nontracking spacing limitations must be adhered to.

Calculate a multiwheel modifier ($M_M$) for each gear configuration selected as described above. $M_M$ is determined by use of Figures 5a and 5b and the equation given below. The following instructions describe the use of Figures 5a and 5b.

**Instructions**

1. Calculate spacings in terms of n and m.
2. Enter the charts (Figures 5a and 5b) and get values for the drag modifiers $(1 - K_n)$, $(1 - K_m)$.

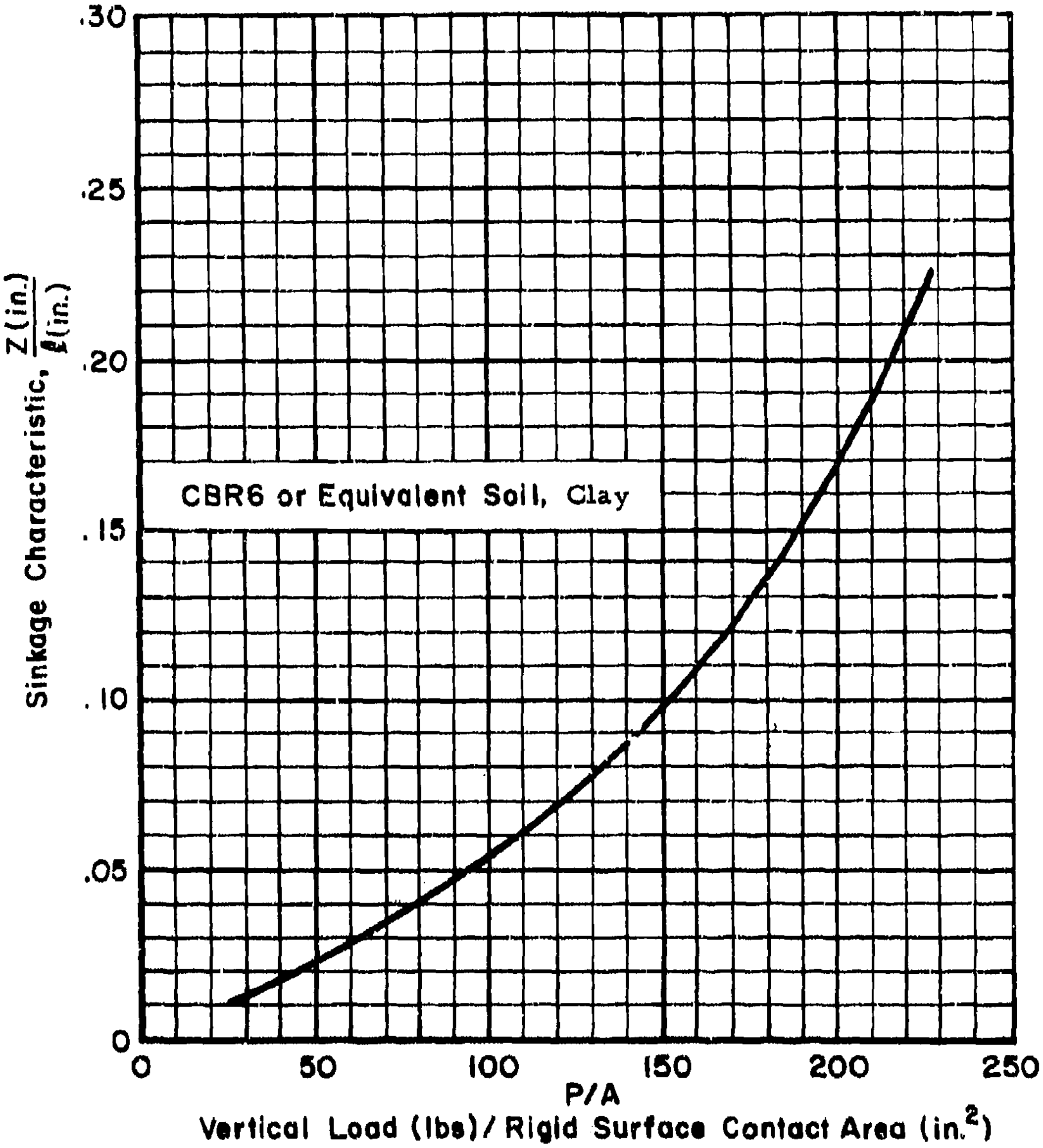


Figure 2. Sinkage Characteristic vs. Vertical Load/Rigid Surface Contact Area

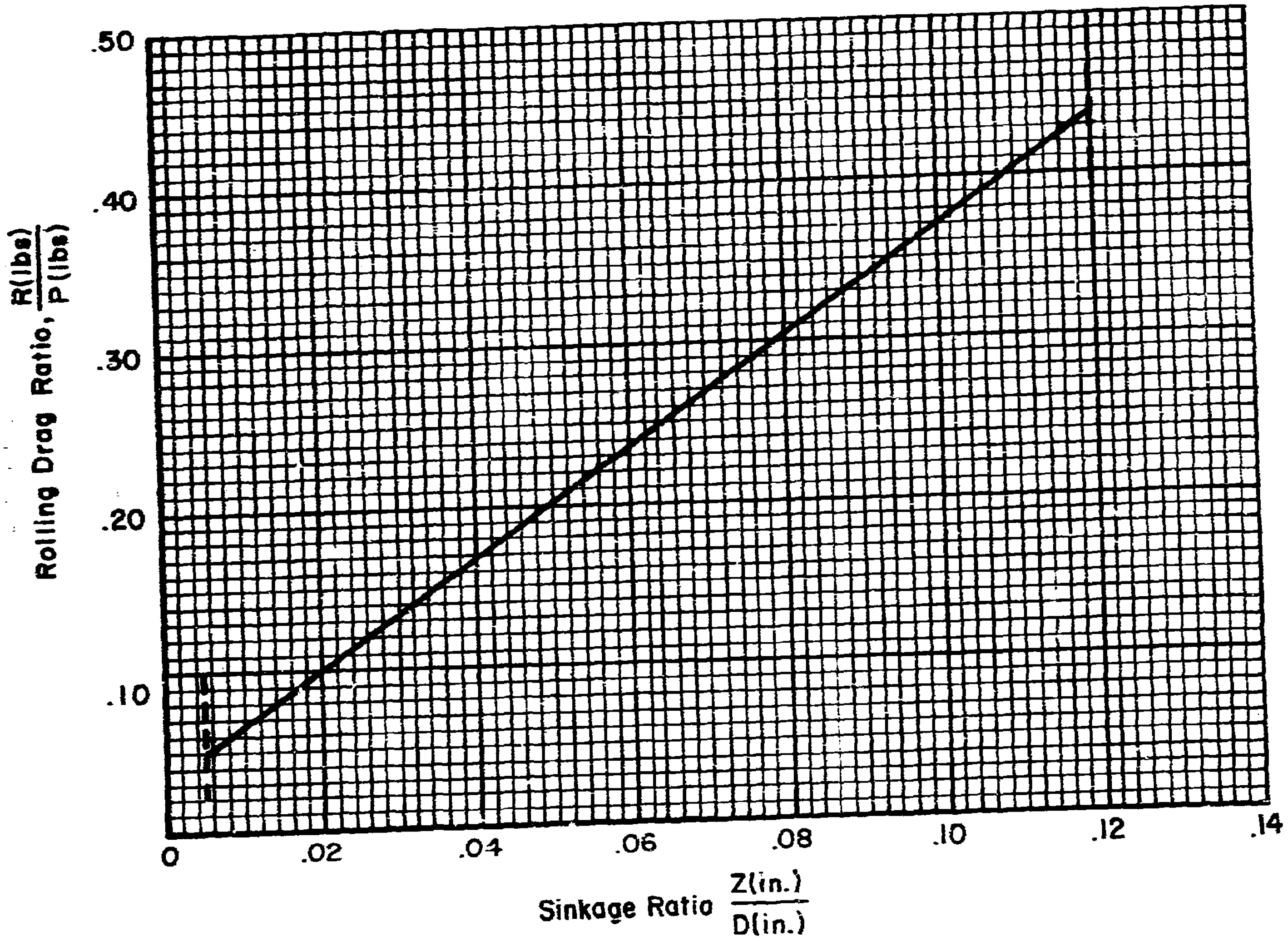
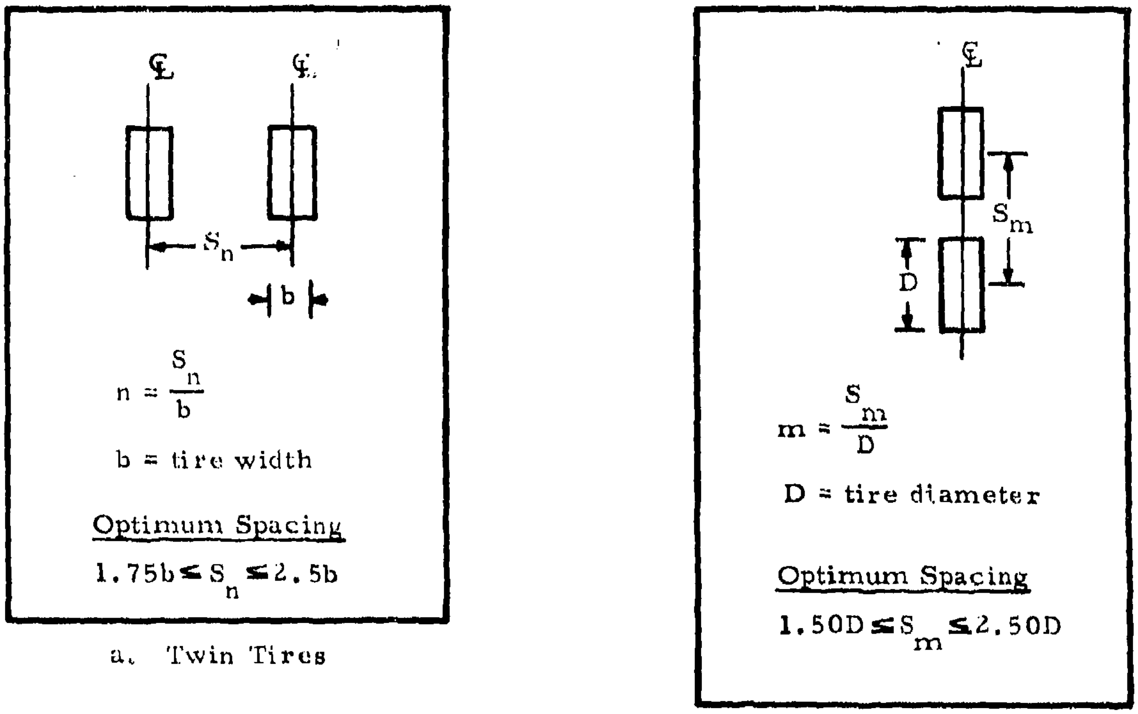


Figure 3. Rolling Drag Ratio vs. Sinkage Ratio, CBR6 Clay Type Soil



$n = \frac{S_n}{b}$

b = tire width

Optimum Spacing

$1.75b \leq S_n \leq 2.5b$

$m = \frac{S_m}{D}$

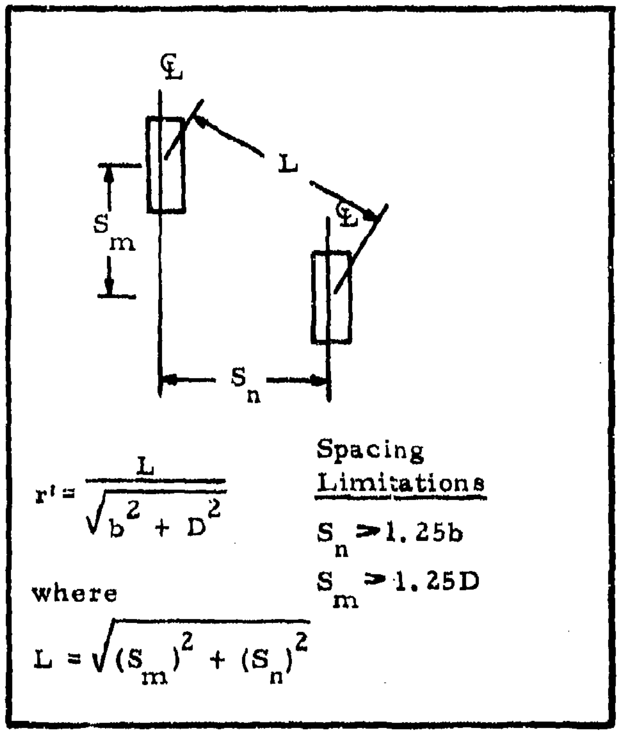
D = tire diameter

Optimum Spacing

$1.50D \leq S_m \leq 2.50D$

a. Twin Tires

b. Tandem-Tracking Tires



$r' = \frac{L}{\sqrt{b^2 + D^2}}$

where

$L = \sqrt{(S_m)^2 + (S_n)^2}$

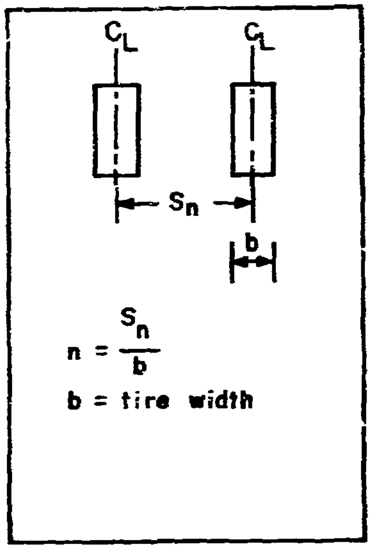
Spacing Limitations

$S_n > 1.25b$

$S_m > 1.25D$

c. Tandem-Nontracking Tires

Figure 4. Optimum Spacings for Multiwheel Configurations for Low Sinkage Conditions (less than 1/2" to 3/4")



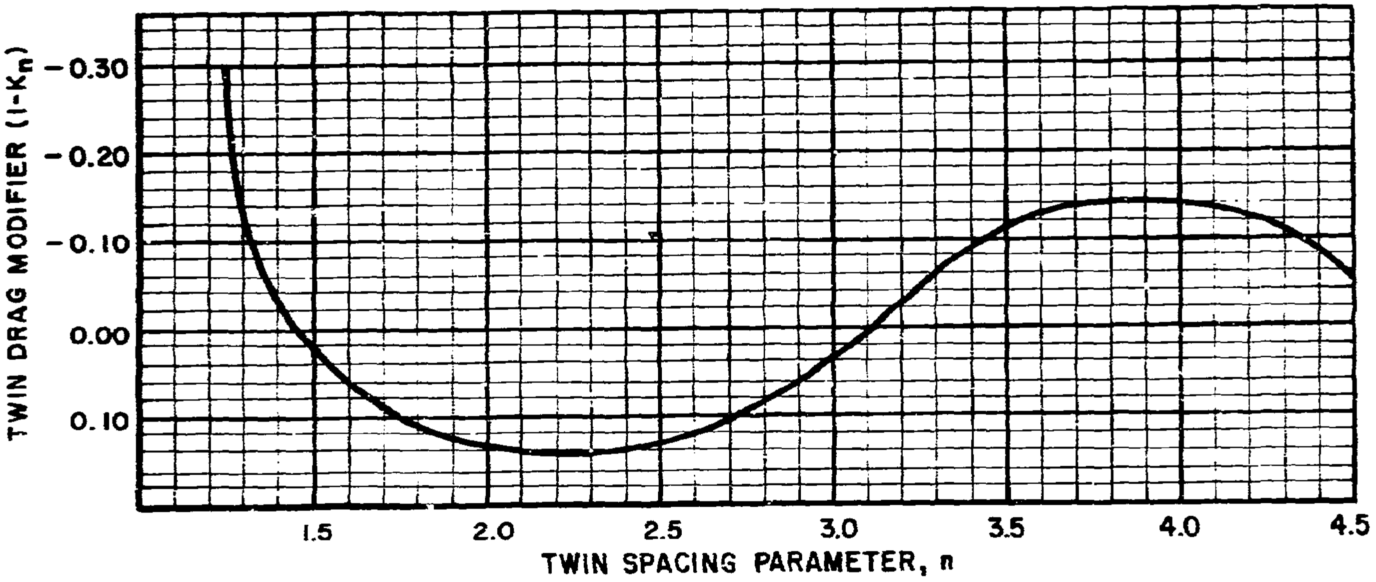
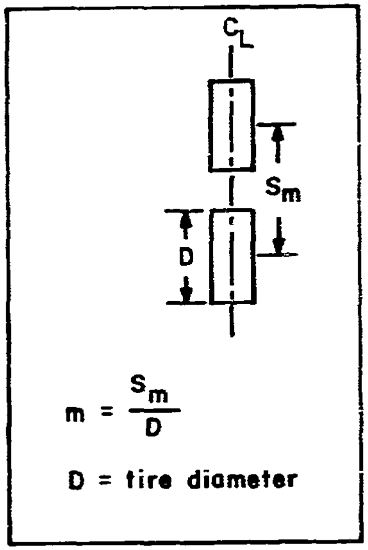


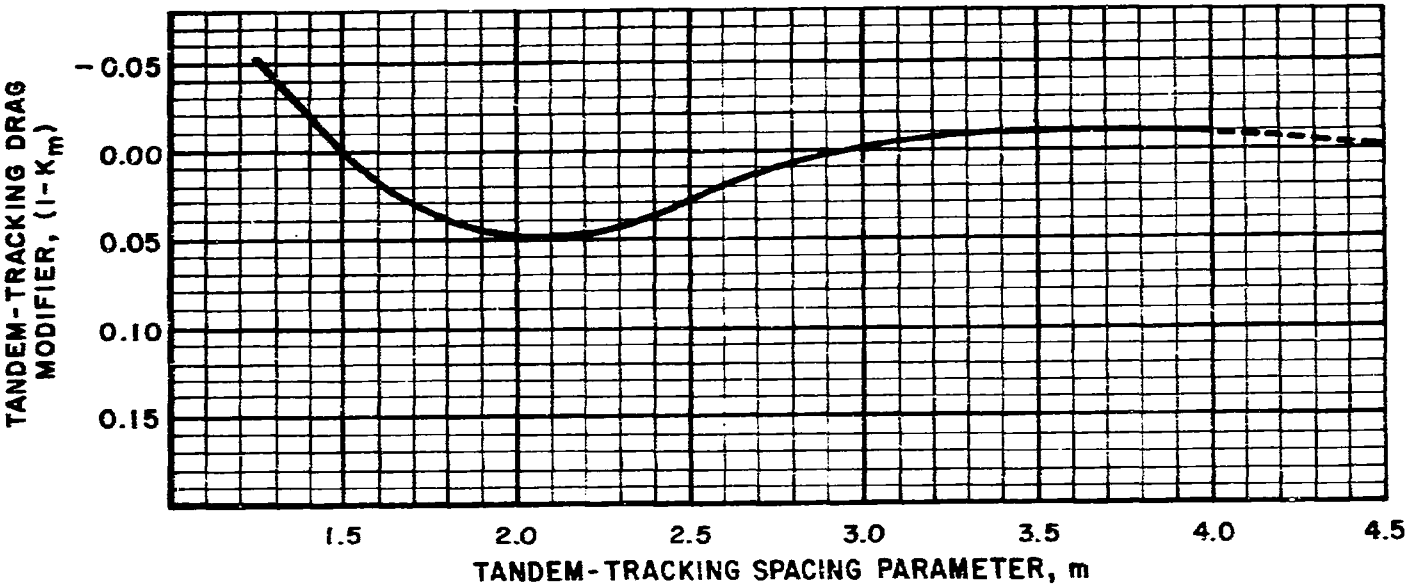
Figure 5a. Multiwheel Drag Modifiers for Low Sinkage Conditions (less than 1/2" to 3/4"), CBR6 Clay Type Soil

Figure 5b. Multiwheel Drag Modifiers for Low Sinkage Conditions (less than 1/2" to 3/4"), CBR6 Clay Type Soil



$m = \frac{S_m}{D}$

D = tire diameter



3. Using the drag modifier values, calculate $M_M$ from the equation below.

$$M_M = 1 - \left[ \frac{N_n}{N} (1 - K_n) + \frac{N_m}{N} (1 - K_m) \right]$$

where

$N$ = total number of wheels per landing gear (main or nose)

$N_n$ = number of wheels (of N) that are in a twin situation

$N_m$ = number of wheels (of N) that are in a tandem-tracking situation

Note: no correction for tandem-nontracking wheels.

This modifier ($M_M$) when multiplied by the $(R/P)_s$ for each gear configuration will determine a rating number $(R/P)_M$ for each of the selected main gear configurations and each of the nose gear configurations. This rating number is also the multiple wheel drag ratio for the gear.

4. Using the value of $(R/P)_M$ for the main and nose gear finally selected, the A/C (R/P) can be calculated based on a weighted average using total static load carried by each gear as defined by

$$A/C\ (R/P) = \frac{\left[(R/P)_{M,\ \text{Main Gear}} \times TSMGL\right] + \left[(R/P)_{M,\ \text{Nose Gear}} \times TSNGL\right]}{TSMGL + TSNGL}$$

where

TSMGL + TSNGL = Gross weight of aircraft for aircraft operation on soil runway.

The A/C (R/P) when multiplied times the total A/C weight (GW) yields the value of the soil drag on the A/C during taxi operations.

## Compute the Number of A/C Passes

From the above group of rated landing gear configurations (nose and main), select a limited number of what appear to be the best candidates for design. The next step is to calculate the number of passes that an aircraft can perform on the CBR6 or equivalent soil runway for each of the design candidates selected from above. Using some of the parameters previously calculated, the following procedure is followed. Note that the single wheel load for the nose gear used in this passes procedure is that shown in Figure 1 for Operations Calculations. The $SWL_N$ used for passes calculation is greater than the $SWL_N$ used for drag determinations due to the greater deterioration of the soil runway associated with the dynamic phenomena of landing operations.

1. Equivalent Single Wheel Load (ESWL)

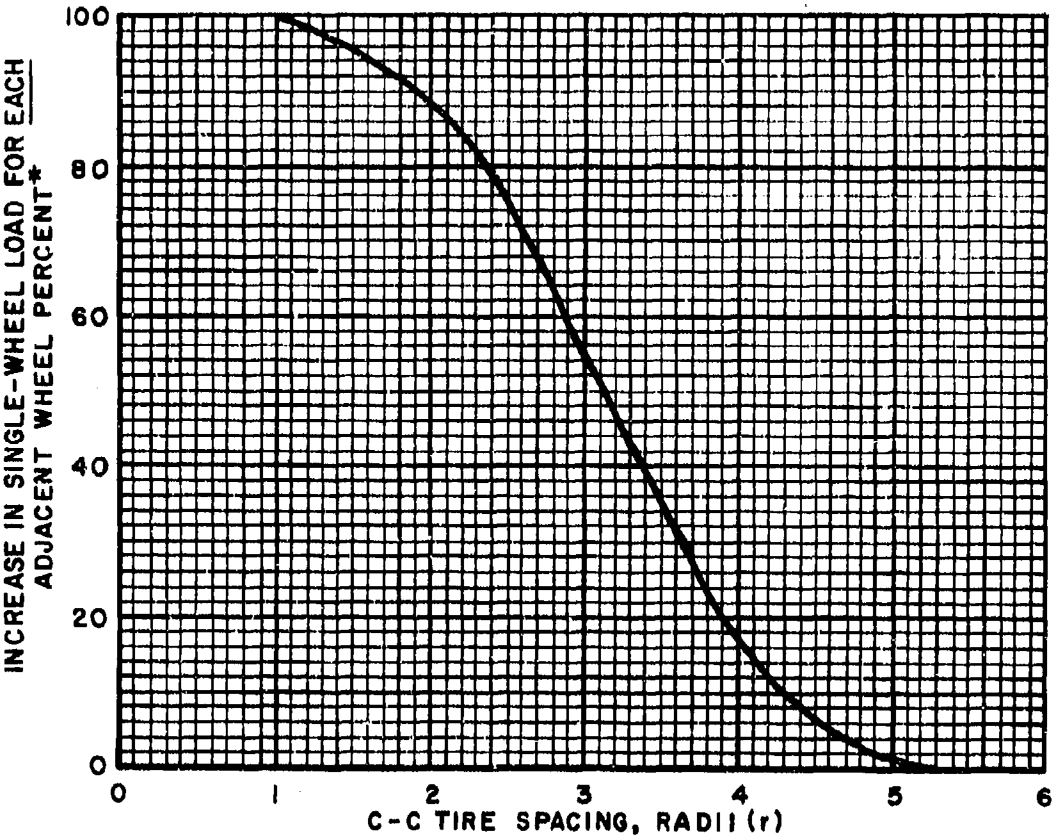
Figure 1, which was used previously, is also used to determine the equivalent single wheel load in the coverage criteria. Determine the center to center spacing in radii by dividing the actual tire spacing by the radius (r) of a circle of area equal to the single tire rigid surface contact area. Increase the single wheel load for <u>each</u> adjacent wheel by the percentage indicated by Figure 6 to determine the equivalent single wheel load (ESWL). This adjacent wheel may be "adjacent" by virtue of either a twin or tandem wheel arrangement. In either case, if it is more than 5-1/2 single tire contact area radii from the wheel under consideration, it will not contribute to any increase in the ESWL. Note that in the case of a landing gear with a single isolated wheel, the ESWL is equal to the single wheel load (SWL).

2. Coverages (C)

Enter Figure 7 with the equivalent single wheel load and tire contact pressure of the assembly in question to determine a value of $CBR_1$ (the CBR required for one coverage). The number of coverages to failure for the CBR6 or equivalent soil runway is then determined by the following relation.

$$\text{Coverages} = \left(\frac{6}{CBR_1}\right)^6$$

Note that the number of coverages calculated by this procedure is based on previously established runway width of 80" plus the width of one main gear bogie and that 75% of the passes are within this runway width. It is further based on a failure criteria of 3" of permanent rut depth. Therefore, the number of passes calculated for a given aircraft does not reflect <u>actual</u>



* Increase in load on a single wheel of a multiple-wheel gear to account for effects of adjacent wheels of the Multiple-wheel gear in arriving at an equivalent single-wheel load.

r = Radius of a circle of area equal to the tire contact area.

Figure 6. Equivalent Single-Wheel Load-Adjustment Curve for Unsurfaced Soils

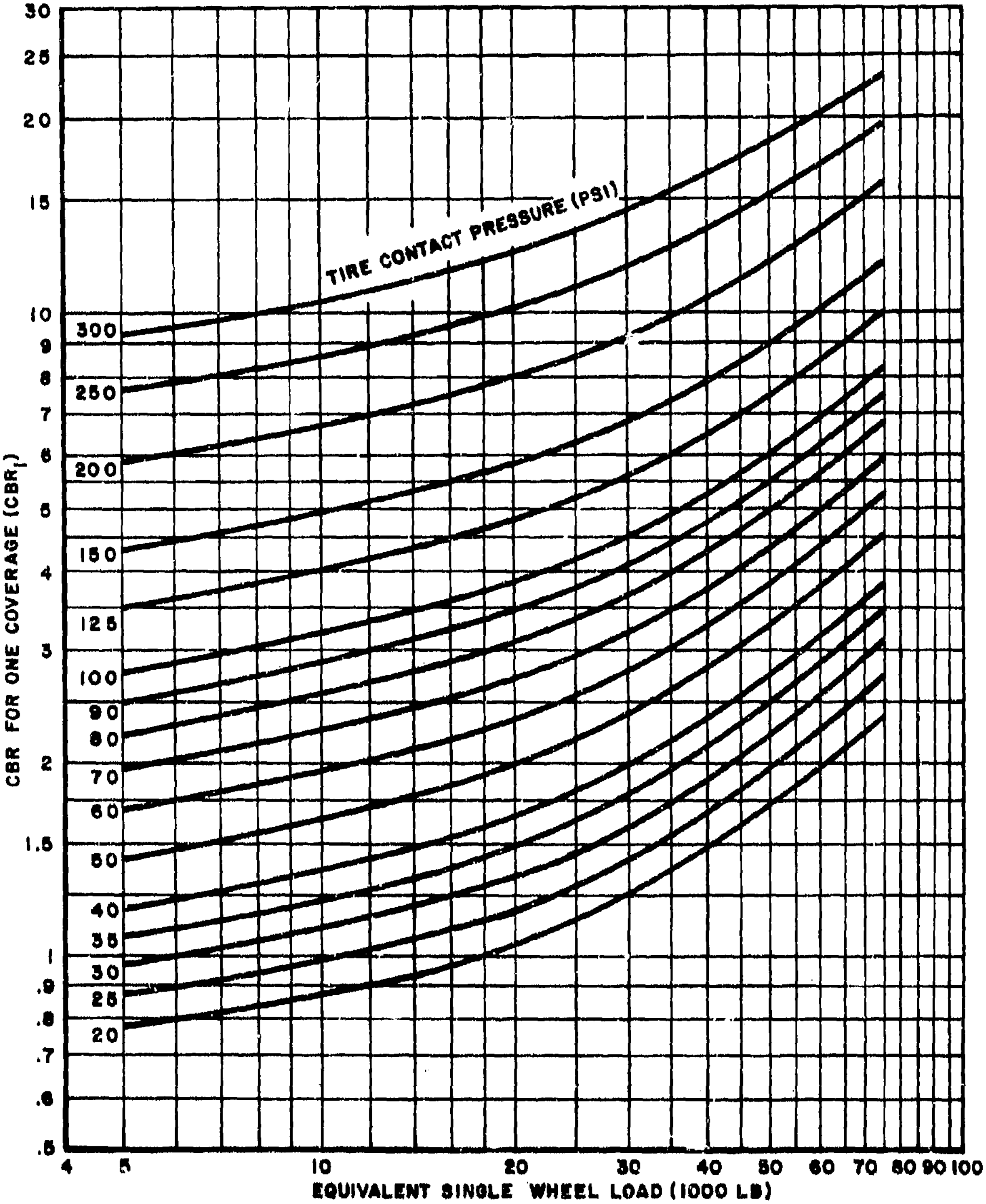


Figure 7. Equivalent Single Wheel Load

number of passes that might be performed but rather the number of rolling passes that an aircraft could perform on a given soil runway up to the defined failure criteria.

3. Passes per Coverage Ratio ($P_a/C$)

Because multiple tire landing gears are very often used in design, a simple relationship does not exist between aircraft passes and aircraft coverages on a soil runway. It is necessary then to convert coverages to passes in order to determine if a candidate landing gear system will satisfy the minimum requirement of 200 passes for the Medium STOL aircraft. Use the procedures of Figure 8 to determine the passes per coverage ($P_a/C$) for each of the assemblies under consideration.

4. Passes ($P_a$)

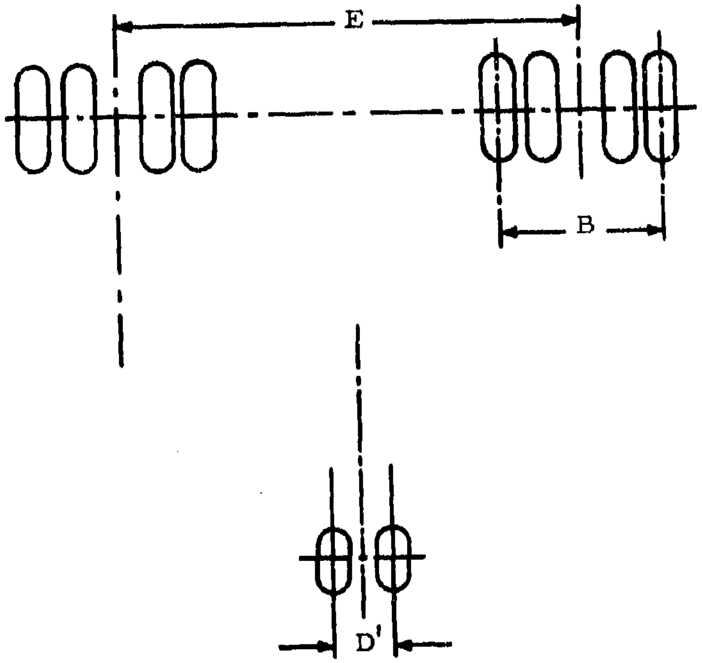
Multiply the number of coverages by the passes per coverage ratio to determine the number of passes that each of the assemblies can accomplish prior to failure of the soil runway.

5. Aircraft Passes (AP)

Use the procedures of Figure 9 to determine the number of passes of the Medium STOL aircraft that can be accomplished prior to failure of the soil runway for each of the landing gear configurations selected for analysis. Each of these configurations should then be listed according to the number of aircraft passes. The configuration with the largest number of aircraft passes is the best landing gear from an operations standpoint. The aircraft is limited by the gear with the minimum number of A/C passes.

## Computation of Braked Tire Drag Ratio

Drag ratios and sinkages associated with braked tire operation on soil are vastly different by comparison to rolling drag ratios and sinkages. Preliminary analytical techniques and braked tire experimental efforts can be utilized to provide preliminary determinations of aircraft tire braking drag ratios ($R_B/P$) for aircraft operating on nonslickened (due to rain) soil runways



### Procedure

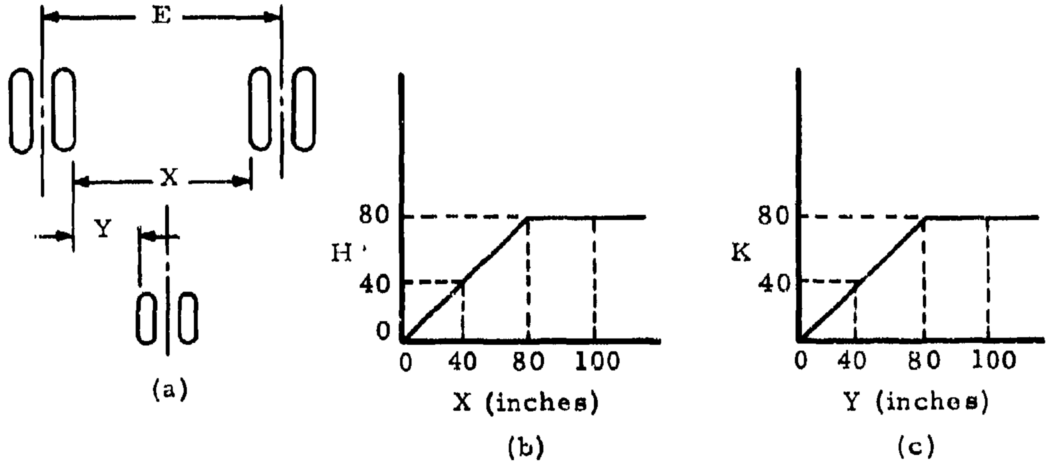
$$\text{Main Assembly: } P_a/C = \frac{B + 80 + W_M}{(0.75)\,(N_M)\,(W_M)}$$

$$\text{Nose Assembly: } P_a/C = \frac{D' + 80 + W_N}{(0.75)\,(N_N)\,(W_N)}$$

### Symbols

| | |
|---|---|
| $P_a/C$ | Passes per Coverage |
| $N_M$ | Number of Tires per Main Gear Bogie |
| $N_N$ | Number of Tires per Nose Gear Assembly |
| $W_M$ | Width of Main Single Tire Contact Area<br>$W_M = 0.874\sqrt{A_M}$ |
| $W_N$ | Width of Nose Single Tire Contact Area<br>$W_N = 0.874\sqrt{A_N}$ |
| $A_M$ | Single Tire Contact Area of Main Tires |
| $A_N$ | Single Tire Contact Area of Nose Tires |

Figure 8. Passes per Coverage



(a) (b) (c)

Procedure

1. Determine dimension

$$X = E - W_M - B$$

$$Y = \frac{E - W_M - W_N - B - D'}{2}$$

2. Use Figure (b) to determine "H" and Figure (c) to determine "K"
3. Compute:

$$AP_M = \frac{80\ P_M\ P_N}{80\ P_N + (80 - H)\ P_N + (80 - K)\ P_M}$$

$$AP_N = \frac{80\ P_M\ P_N}{80\ P_M + (80 - H)\ P_N + (80 - K)\ P_N}$$

where

$P_M$ = allowable passes for the main gear

$P_N$ = allowable passes for the nose gear

4. The allowable number of aircraft passes (AP) is then equal to the smaller value, $AP_M$ or $AP_N$.
5. All dimensions are in inches.

Figure 9. Number of Aircraft Passes

in the lower velocity range (less than 15 knots). The results of previously conducted test programs(4,7) were used together with a CBR6 soil strength to develop the following braking equation.

$$\frac{R_B}{P} = 10.0\left(\frac{Z}{D}\right) + \frac{45.0\,D^2}{P}\left(\frac{Z}{D}\right)^{1/2}\left(\frac{S}{100}\right)^{1/2}$$

for $0.01 \leqslant \frac{Z}{D} \leqslant 0.06$, where

$\left(\frac{Z}{D}\right)$ is the sinkage ratio previously calculated for a given rolling tire

P = vertical load on the tire (reference to Figure 1 - $SWL_M$ or $SWL_N$)

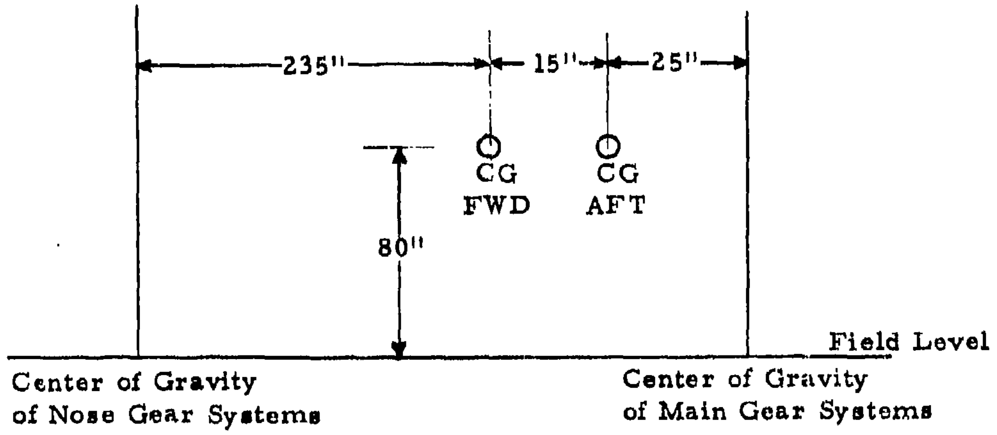
S = percent tire slip

The braking drag ratio should be determined for each of the candidate tires and the results listed according to the magnitude of $R_B/P$. The aircraft tire with the maximum $R_B/P$ will provide the shortest stopping distance due to braked tire/soil interaction for the aircraft in a braking mode. Note that braked tire sinkages will range from two to four times rolling sinkages (the above equation accounts for this phenomena) and that the maximum $R_B/P$ in the above equation will occur at a slip value of between 90 to 100%. This differs markedly from rigid surface braked tire performance in that an aircraft on pavement normally obtains maximum braking resistance at approximately 30% slip. Aircraft with systems that actually limit slip to less than 90 to 100% in soil (i.e., anti-skid systems), will experience a braking resistance that can be calculated from the above equation by using the appropriate value for "S".

## SECTION IV

## TYPICAL DESIGN EXAMPLE

The following example will run through the procedure described in Section II for a single tire selection for the main gear (tricycle gear), and a single tire selection for the nose gear. A 100,000 pound aircraft will be used for this example with the wheel base and center of gravity locations as shown below. Note that these dimensions must be approximated for the calculations that follow if they are not known.



### Horizontal Drag Ratio Calculation

1. Tire Selection

| Nose Tire Selection | Main Tire Selection |
|---|---|
| 9.50-16 Type III | 12.50-16 Type III |
| D = 33.4" | D = 38.5" |
| $D_F$ = 18.0" | $D_F$ = 18.5" |
| $\delta$ = 35% | $\delta$ = 35% |
| b = 9.7" | b = 12.75" |
| Rated Static Load = 9250# | Rated Static Load = 12800# |
| Max. Allow. Load = 0.80* x 11200 = 8960# | |

---

* A reduction factor is often used in design to permit a weight growth in later production models of certain aircraft.

From Figure 1:

$$TSNGL = \frac{100{,}000(25)}{275} = 9091\#$$

$$N_N = \frac{9091}{8960} = 1.01$$

Use 2 Nose Tires

From Figure 1:

$$TSMGL = \frac{100{,}000(250)}{275} = 90909\#$$

$$N_M = \frac{90909}{12800} = 7.1$$

Use 8 Main Tires

2. Single Tire Parameters

Nose Tire Selection

$$d = \frac{35 \cdot (33.4-18)}{200}$$

$$= 2.7''$$

$$\ell = 1.7\sqrt{2.7(33.4-2.7)}$$

$$= 15.5''$$

$$A = 2.36 \cdot 2.7\sqrt{(33.4-2.7)(9.7-2.7)}$$

$$= 93.4 \text{ sq. in.}$$

See Figure 1, Part B

$$SWL_N = \frac{100{,}000(25)}{275 \times 2} = 4545\#$$ (load per nose tire)

$$\frac{P}{A} = \frac{4545}{93.4} = 48.7 \text{ psi}$$

From Figure 2:

$$\frac{Z}{\ell} = .022$$

$$\frac{Z}{D} = .022 \times 15.5 \times \frac{1}{33.4}$$

$$= 0.010$$

From Figure 3:

$$\left(\frac{R}{P}\right)_s = 0.07$$

Main Tire Selection

$$d = \frac{35 \cdot (38.5-18.5)}{200}$$

$$= 3.5''$$

$$\ell = 1.7\sqrt{3.5(38.5-3.5)}$$

$$= 18.8''$$

$$A = 2.36 \cdot 3.5\sqrt{(38.5-3.5)(12.75-3.5)}$$

$$= 148.6 \text{ sq. in.}$$

See Figure 1, Part A

$$SWL_M = \frac{100{,}000(250)}{275 \times 8} = 11364\#$$ (load per main tire)

$$\frac{P}{A} = \frac{11364}{148.6} = 76.5 \text{ psi}$$

From Figure 2:

$$\frac{Z}{\ell} = .039$$

$$\frac{Z}{D} = .039 \times 18.8 \times \frac{1}{38.5}$$

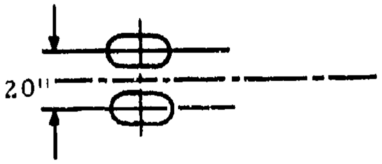
$$= 0.019$$

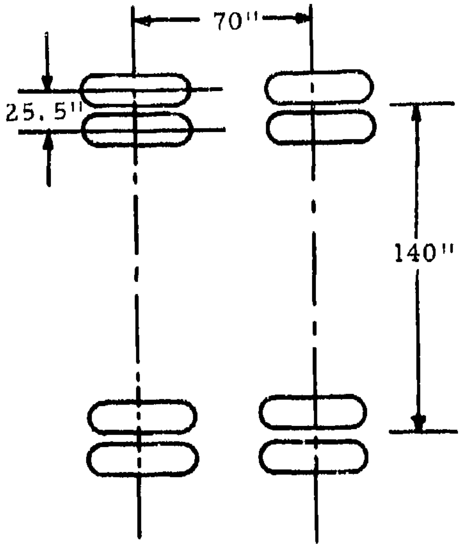
From Figure 3:

$$\left(\frac{R}{P}\right)_s = 0.095$$

### 3. Multiwheel Configuration

The configuration shown is one possible solution chosen abritrarily from many possibilities. Note that the spacings given in Figure 4 were used.





### 4. Multiwheel Modifier

From Figures 5a and 5b:

**Nose Gear**

$$n = \frac{20''}{9.7''} = 2.06 \text{ (use 2.1)}$$

$$m = 0$$

$$(1 - K_n) = 0.13$$

$$(1 - K_m) = \text{does not apply}$$

$$M_M = 1 - \left[ + \frac{2}{2} (0.13) \right]$$

$$= 0.87$$

$$\left(\frac{R}{P}\right)_M = \left(\frac{R}{P}\right) \times 0.87$$

$$\left(\frac{R}{P}\right)_M = 0.061$$

From Figures 5a and 5b:

**Main Gear**

$$n = \frac{25.5}{12.75} = 2$$

$$m = \frac{70}{38.5} = 1.82$$

$$(1 - K_n) = 0.13$$

$$(1 - K_m) = 0.04$$

$$M_M = 1 - \left[ + \frac{4}{4} (0.13) + \frac{4}{4} (0.04) \right]$$

$$= 0.83$$

$$\left(\frac{R}{P}\right)_M = \left(\frac{R}{P}\right) \times 0.83$$

$$\left(\frac{R}{P}\right)_M = 0.079$$

## Calculation of Average Aircraft Drag Ratio

Using the multiwheel drag ratio, $(R/P)_M$, for the main and nose gear, the total aircraft drag can be calculated. This value divided by the aircraft weight will be the average aircraft drag ratio value, A/C $(R/P)_M$. For the previous example:

Drag on Nose

$$\text{Drag N} = .061 \times 2 \times 4545$$
$$= 554\#$$

Drag on Main

$$\text{Drag M} = .079 \times 8 \times 11364$$
$$= 7182\#$$

$$\text{Total Drag} = 554 + 7182 = 7736$$

$$\text{A/C } (R/P)_M = \frac{7736}{100{,}000} = 0.08$$

## Aircraft Operations - Passes Calculation

1. Equivalent Single Wheel Load (ESWL)

Nose Gear

$$r_n = .564\sqrt{A}$$
$$= .564\sqrt{93.4}$$
$$= 5.45''$$

$$\frac{\text{wheel spacing}}{r_n} = \frac{20''}{5.45''} = 3.67$$

From Figure 1, Part B (Operations SWL):

$$SWL_N = \frac{100{,}000(40)}{275 \times 2} + \frac{10 \times 100{,}000 \times 80}{32.2 \times 275 \times 2}$$

$$SWL_N = 11{,}789\#$$

From Figure 6:

$$ESWL_N = SWL_N + \text{Factor}$$
$$= 11789 + 29\%$$
$$= 15208\#$$

Main Gear

$$r_m = .564\sqrt{A}$$
$$= .564\sqrt{148.6}$$
$$= 6.88''$$

$$\frac{\text{twin wheel spacing}}{r_m} = \frac{25.5''}{6.88''} = 3.71$$

or

$$\frac{\text{tandem wheel spacing}}{r_m} = \frac{70''}{6.88''} \approx 10 \text{ (no influence from tandem tires)}$$

From Figure 6:

$$ESWL_M = SWL_M + \text{Factor}$$
$$= 11364 + 27\%$$
$$= 14434\#$$

## 2. Coverage Calculation

### Nose Gear

From Figure 7:

for $ESWL_N = 15208\#$

and $\frac{SWL_N}{A} = 126.2$ psi (tire contact pressure)

obtain $CBR_1 \approx 4.5$

for $CBR = 6$

$$C_N = \left(\frac{6}{4.5}\right)^6$$

$= 5.6$ coverages

### Main Gear

From Figure 7:

for $ESWL_M = 14434\#$

and $\frac{SWL_M}{A} = 76.5$ psi

obtain $CBR_1 \approx 2.7$

for $CBR = 6$

$$C_M = \left(\frac{6}{2.7}\right)^6$$

$= 120$ coverages

## 3. Passes Per Coverage Ratio (P/C)

### Nose Gear

From Figure 8:

$$W_N = .874 \cdot \sqrt{93.4 \text{ in.}^2}$$

$= 8.45''$

$$\frac{P_a}{C} = \frac{20 + 80 + 8.45}{0.75 \times 2 \times 8.45}$$

$= 8.56$

### Main Gear

From Figure 8:

$$W_M = .874 \cdot \sqrt{148.6 \text{ in.}^2}$$

$= 10.65''$

$$\frac{P_a}{C} = \frac{25.5 + 80 + 10.65}{0.75 \times 4 \times 10.65}$$

$= 3.62$

## 4. Passes Calculation

### Nose Gear

$P_N = 5.6 \times 8.56 = 47.9$

### Main Gear

$P_M = 120 \times 3.62 = 434$

## Aircraft Passes

From Figure 9 (also refer to Figure 8 for symbol notation)

$X = 140 - 10.65 - 25.5$

$= 104''$

$H = 80$ (see Figure 9)

$$Y = \frac{140 - 10.65 - 8.45 - 25.5 - 20}{2}$$

$= 37.7''$

$K = 37.7''$ (see Figure 9)

$$AP_M = \frac{80 \times 434 \times 47.9}{80 \times 47.9 + (80 - 80)\ 47.9 + (80 - 37.7) \times 434}$$

$$= 76$$

$$AP_N = \frac{80 \times 434 \times 47.9}{80 \times 434 + (80 - 80)\ 47.9 + (80 - 37.7) \times 47.9}$$

$$= 45$$

Therefore, the maximum allowable passes for the aircraft = 45.

## Calculation of Braked Tire Drag Ratio (for S = 25%)

### Nose Gear

(use only if aircraft is equipped with nose gear braking)

From previous calculations

$$\frac{Z}{D} = 0.010$$

Therefore,

$$\frac{R_B}{P} = 10\ (0.010) \ + \frac{45\ (33.4)^2}{4545}\ (0.010)^{1/2} \left(\frac{25}{100}\right)^{1/2}$$

$$\frac{R_B}{P} = 0.100 \ + 0.552$$

$$\frac{R_B}{P} = 0.65 \quad \text{(assuming S = 25\%)}$$

### Main Gear

From previous calculations

$$\frac{Z}{D} = 0.019$$

Therefore,

$$\frac{R_B}{P} = 10\ (0.019) \ + \frac{45\ (38.5)^2}{11364}\ (0.019)^{1/2} \left(\frac{25}{100}\right)^{1/2}$$

$$\frac{R_B}{P} = 0.190 + 0.404$$

$$\frac{R_B}{P} = 0.59 \quad \text{(assuming S = 25\%)}$$

# SECTION V

# COMPUTER PROGRAM AND TEST CASE

## 1. Computer Program

The computer program for determining the design procedure for establishing aircraft capability to operate on soil surface has been written and debugged. The computer program was set up for an aircraft with a tricycle type landing gear configuration. A general flow chart of the computer program is shown in Figure 10. A Fortran IV source program listing of the computer program, a list of definition of symbols, and some remarks about running the program are given in paragraphs 4, 5, and 6.

## 2. Test Case

The computer program is presently being used for calculating the following case, which has load, tires, and aircraft parameters the same as in the example in Section III.

| | |
|---|---|
| Number of Test Cases Run: | DASET = 1 |
| Load Parameters: | |
| Gross Weight | GW = 100,000 pounds |
| Deflection of Nose Tires | DE = 35% |
| Deflection of Main Tires | DEM = 35% |
| Percent of Slip | S = 25% |
| Tire Parameters: | |
| Diameter of Nose Tires | DN = 33.4 inches |
| Rim Diameter of Nose Tires | DFN = 18.0 inches |
| Section Width of Nose Tires | BN = 9.7 inches |
| Number of Nose Tires | NN = 2.0 |
| Diameter of Main Tires | DM = 38.5 inches |
| Rim Diameter of Main Tires | DFM = 18.5 inches |
| Section Width of Main Tires | BM = 12.75 inches |
| Nose Gear Tire Type | TN = 3 |
| Main Gear Tire Type | TM = 3 |

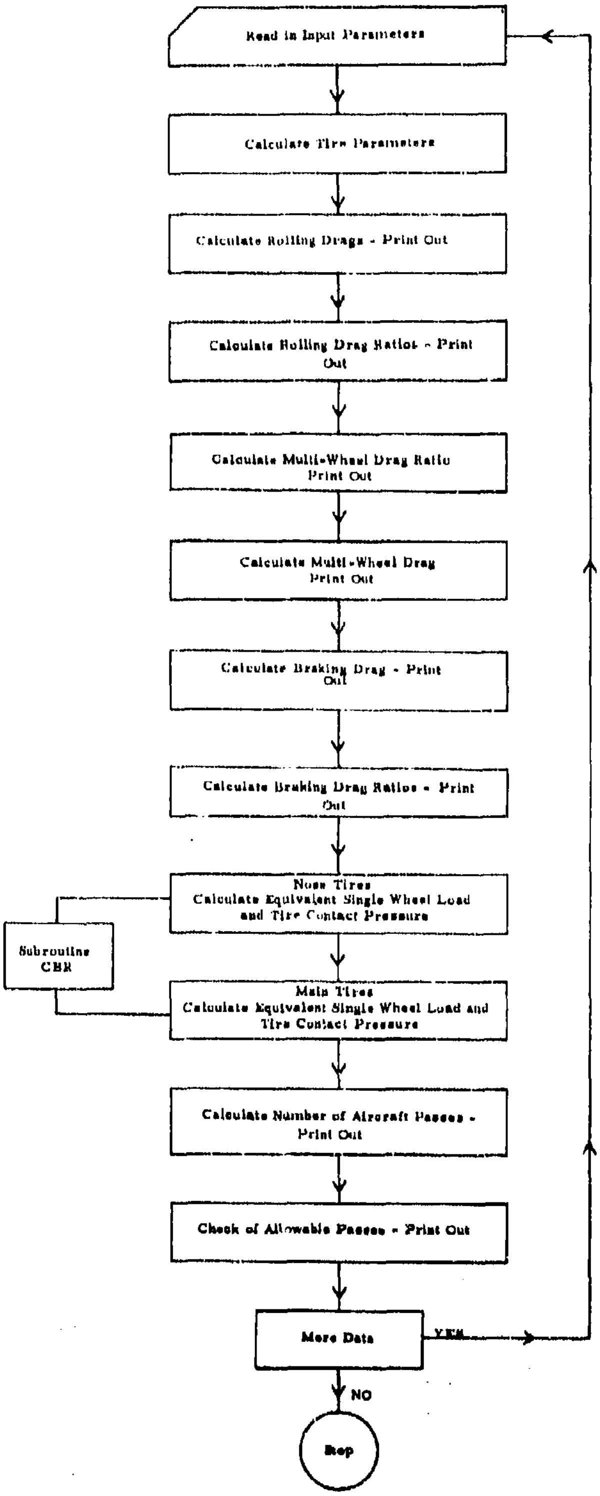


Figure 10. General Flow Chart of the Computer Program

| | |
|---|---|
| Nose Gear Tire Type | TN = 3 |
| Main Gear Tire Type | TM = 3 |
| Number of Main Tires in a Tandem-Tracking Situation | NM1 = 4 |
| Number of Main Tires in a Twin Situation | NN1 = 4 |

Aircraft Parameters:

| | |
|---|---|
| Distance from Center of Gravity of Nose Gears to Center of Gravity of FWD | L = 235.0 inches |
| Distance from Center of Gravity of Nose Gear to Center of Gravity of AFT | LL = 250.0 inches |
| Distance from Center of Gravity of Nose Gear to Center of Gravity of Main Gear | F = 275.0 inches |
| Distance from Center of Gravity of Main Gears to Center of Gravity of FWD | M = 25.0 inches |
| Distance from Center of Gravity from Ground Level to Center of Gravity of FWD | U = 80.0 inches |
| Distance from Center of Gravity of One Main Gear to Center of Gravity of the Other Main Gear | E = 140.0 inches |
| Distance from outer tire to outer tire twin type of spacing within a main gear (see Figure 8) | B1 = 25.5 inches |
| Spacing of nose tires (see Figure 5a) | SN = 20.0 inches |
| Spacing of Tandem-Tracking Tires - Main | SNM = 25.5 inches |
| Spacing of Twin Tires - Main | SM = 70.0 inches |

## 3. Test Results and Discussion

Comparison of these results to the hand calculated results in Section III were made and demonstrated the speed and accuracy of the computer program. When the computer turn around time is small, or when the program can be operated on a time-share remote terminal setup, the utilization of the computer program to calculate many different configurations, tires, and aircraft types will significantly benefit the user. Although the program is set up for a tricycle configuration, the program can be modified for other types of configurations for which the user may be designing.

## 4. Procedure for Running the Computer Program

1. Specify the first four data cards:

First Card - Specify number of test case runs.

Second Card - Specify four parameters: gross weight (lbs.), deflection of nose tires, deflection of main tires, slip.

Third Card - Specify seven tire parameters: diameter of nose tires (inches), rim diameter of nose tires (inches), section width of nose tires (inches), number of nose tires, diameter of main tires (inches), rim diameter of main tires (inches), section width of main tires (inches).

Fourth Card - Specify two tire types: nose tires, main tires.

Fifth Card - Specify four main tire parameters: total number of main tires, number of tires per main bogie, number of tires that are in a tandem-tracking situation, number of tires that are in a twin situation.

Sixth Card - Specify ten aircraft parameters: (L) distance from center of gravity of nose gear to center of gravity

FWD (inches), (L') distance from center of gravity of nose gear to center of gravity of AFT (inches), (F) distance from center of gravity of nose gear to center of gravity of main gear (inches), (M) distance from center of gravity of main gear to center of gravity FWD (inches), (J) distance from ground level to center of gravity of one main gear to center of gravity of the other main gear (inches), (B) distance from outer tire to outer tire twin type spacing within a main gear (inches), ($S_N$) spacing of nose tires (inches), ($S_N$) spacing of tandem-tracking tires-main gear (inches), ($S_M$) spacing of twin tires-main gear (inches).

2. With the second, third, and sixth input cards, the input is to be typed in as real values. The input data on the first, fourth, and fifth cards is to be typed in as integers.

3. To make more than one continuous run, additional cards with the same information as data cards 1, 2, 3, 4, 5, and 6 must be inserted behind the original set of data.

## 5. Fortran IV Source Program Listing

(Fortran IV Program is on the succeeding pages)

```
      PROGRAM DPEAC (INPUT, OUTPUT,TAPE 5=INPUT)
      REAL NN,L,M,L1,K1,N2,N3,M1,MM1,MM2,L2,LL
      REAL MA,MI
      REAL A(17,12)
      INTEGER TYPE,TN,TM,DASET
C     DESIGN PROGRAM SETUP FOR CBR6 OR EQIVALENT TYPE OF SOIL
      READ (5,121) DASET
121   FORMAT (I10)
      DO 600 LN=1,DASET
      READ (5,100) GW,DE,DEM,S
100   FORMAT (4F9.2)
      READ (5,105)  DN,DFN,BN,NN,DM,DFM,BM
105   FORMAT (7F9.2)
      READ (5,103) TN,TM
103   FORMAT (2I9)
      READ (5,110)  NM,N1,NM1,NN1
110   FORMAT (4I9)
      READ (5,115)  L,LL,F,M,U,E,B1,SN,SNM,SM
115   FORMAT (10F8.2)
      DATA((A(J,I),I=1,12),J=1,17)/400.,5.,7.,10.,14.,20.,25.,30.,40.,
     150.,60.,70.,300.,9.3,9.8,10.8,11.5,13.,13.5,14.5,17.,18.5,20.5,
     222.5,250.,7.7,8.1,8.7,9.3,10.5,11.,12.,13.5,15.5,17.,19.5,
     3200.,5.9,6.25,6.7,7.3,8.,8.6,9.2,10.5,12.5,13.5,15.,
     4150.,4.3,4.6,4.9,5.4,5.8,6.3,6.8,7.9,9.,10.,12.,
     5125.,3.5,3.75,4.,4.4,4.8,5.3,5.6,6.5,7.5,8.5,9.5,
     6100.,2.8,2.95,3.2,3.4,3.9,4.3,4.5,5.25,6.,6.9,7.9,
     790.,2.5,2.7,2.9,3.2,3.5,3.8,4.1,4.8,5.5,6.3,7.1,
     880.,2.25,2.4,2.6,2.8,3.1,3.4,3.7,4.3,5.,5.7,6.5,
     970.,1.95,2.1,2.3,2.45,2.7,2.9,3.25,3.75,4.4,5.,5.7,
     A60.,1.7,1.8,1.9,2.2,2.4,2.6,2.8,3.3,3.8,4.4,5.,
     B50.,1.4,1.55,1.68,1.8,2.,2.2,2.4,2.85,3.3,3.8,4.3,
     C40.,1.2,1.29,1.35,1.48,1.7,1.8,2.,2.4,2.8,3.1,3.6,
     D35.,1.1,1.15,1.23,1.3,1.5,1.65,1.8,2.1,2.5,2.9,3.3,
     E 30.,0.97,1.1,1.15,1.2,1.3,1.45,1.6,1.85,2.25,2.6,2.9,
     F25.,0.88,.92,.99,1.1,1.20,1.3,1.40,1.7,1.95,2.25,2.6,
     G20.,0.78,.82,.87,.93,1.1,1.15,1.25,1.5,1.75,2.,2.25/
      PRINT 4
      FORMAT (*1*,*PROGRAM COMPUTES ROLLING DRAG, MULTI-WHEEL DRAG,BRAKED DRAG,
     1AND NUMBER OF AIRCRAFT PASSES FOR A M/STOL AIRCRAFT*)
      TSNGL=(GW*(F-LL))/F
      SWLN = TSNGL/NN
      SWLN1=(GW*(F-L)/(F*NN))+((10*GW*U)/(32.2*F*NN))
      TSMGL=(GW*(F-M))/F
      SWLM=TSMGL/NM
      D1=(DE*(DN-DFN))/2.0
      L1=1.7*SQRT(D1*(DN-D1))
      TYPE=TN
      MA=2*SQRT(D1*(DN-D1))
      MI=2*SQRT(D1*(BN-D1))
      FMA=0.85*MA
      IF(TYPE.LT.6) GO TO 15
      CCEF=1.0
      GO TO 16
15    IF(TYPE.LT.3) GO TO 17
      CCEF=0.93
```

```
      GO TO 16
17    COEF=0.84
16    FMI=MI*COEF
      IF(TYPE.GT.1) GO TO 18
      COEF1=0.85
      GO TO 19
18    COEF1=0.95
19    A1=0.785*FMA*FMI*COEF1
      D2=(DEM*(DM-DFM))/200
      L2=1.7*SQRT(D2*(DM-D2))
      TYPE=TM
      MA=2*SQRT(D2*(DM-D2))
      MI=2*SQRT(D2*(BM-D2))
      FMA=0.85*MA
      IF(TYPE.LT.6) GO TO 25
      COEF=1.0
      GO TO 26
25    IF(TYPE.LT.3) GO TO 27
      COEF=0.93
      GO TO 26
27    COEF=0.84
26    FMI=MI*COEF
      IF(TYPE.GT.1) GO TO 28
      COEF1=0.85
      GO TO 29
28    COEF1=0.95
29    A2=0.785*FMA*FMI*COEF1
      CP1=SWLN/A1
      ZL1=CP1/(2419.64-(5.96207*CP1))
      ZD1=(ZL1*L1)/DN
      RPSN=0.032533+(3.37572*ZD1)
      CP2=SWLM/A2
      ZL2=CP2/(2419.64-(5.96207*CP2))
      ZD2=(ZL2*L2)/DM
      RPSM=0.032533 + (3.37572*ZD2)
      N2=SN/BN
      Y1A=0.354336-(0.732081*N2)-(0.0525284*N2**2)
      Y1B=(0.697306*N2**3)-(0.405064*N2**4)
      Y1C=(0.0861469*N2**5)-(0.00631667*N2**6)
      Y=Y1A+Y1B+Y1C
      MM1=1-Y
      RPN=RPSN*MM1
      ACRPN=RPN*TSNGL
      N3=SNM/BM
      Y2A=0.354336-(0.732081*N3)-(0.0525284*N3**2)
      Y2B=(0.697306*N3**3)-(0.405064*N3**4)
      Y2C=(0.0861469*N3**5)-(0.00631667*N3**6)
      Y2=Y2A+Y2B+Y2C
      M1=SM/DM
      Y3A=-0.19264-(0.448567*M1)+(0.952061*M1**2)
      Y3B=(-0.53968*M1**3)+(0.122637*M1**4)
      Y3C=-0.00985133*M1**5
      Y3=Y3A+Y3B+Y3C
      MM2=1-(((NN1/N1)*Y2)+((NM1/N1)*Y3))
      RPM=RPSM*MM2
```

```
      ACRPM=RPM*TSMGL
      ACRPT=ACRPN + ACRPM
      RPT=ACRPT/(TSNGL + TSMGL)
      RPSN1=RPSN*SWLN
      RPSM1=RPSM*SWLM
      PRINT1
1     FORMAT (*-*,*SINGLE WHEEL ROLLING DRAG, LBS.*)
      PRINT2
2     FORMAT (* *,*-------------------------*)
      PRINT3
3     FORMAT (*0*,*NOSE TIRES                   MAIN TIRES*)
      PRINT 60,RPSN1,RPSM1
60    FORMAT(* *,F8.2,16X,F8.2)
      PRINT 132
132   FORMAT (*-*,*SINGLE WHEEL ROLLING DRAG RATIO, (R/P)S*)
      PRINT 133
133   FORMAT (* *,*-------------------------------*)
      PRINT 134
134   FORMAT (*0*,*NOSE TIRES                   MAIN TIRES *)
      PRINT 135,RPSN,RPSM
135   FORMAT (* *,2X,F5.3,18X,F5.3)
      PRINT 200
200   FORMAT (*-*,*MULTI-WHEEL DRAG RATIO, (R/P)M*)
      PRINT 202
202   FORMAT (* *,*----------------------*)
      PRINT 204
204   FORMAT (*0*,*NOSE TIRES                   MAIN TIRES            AIRCRAFT*)
      PRINT 206,RPN,RPM,RPT
206   FORMAT (* *,2X,F5.3,18X,F5.3,13X,F5.3)
      PRINT 208
208   FORMAT (*-*,*MULTI-WHEEL DRAG, LBS.*)
      PRINT 210
210   FORMAT (* *,*----------------*)
      PRINT 212
212   FORMAT (*0*,*NOSE TIRES                   MAIN TIRES            AIRCRAFT*)
      PRINT 214, ACRPN,ACRPM,ACRPT
214   FORMAT (* *,1X,F8.2,16X,F8.2,10X,F8.2)
      RBPN=(10.0*ZC1)+(((45*DN**2)/SWLN )*SQRT(ZC1)*SQRT(S/100))
      RBPN1 = RBPN*SWLN
      RBPM=(10.0*ZC2)+(((45*DM**2)/SWLM)*SQRT(ZC2)*SQRT(S/100))
      RBPM1 = RBPM*SWLM
      PRINT 136
136   FORMAT (*-*,*AIRCRAFT BRAKED DRAG, LBS.*)
      PRINT 137
137   FORMAT (* *,*---------------------*)
      PRINT 170,S
170   FORMAT (* *,*FOR S=*,F4.0)
      PRINT 138
138   FORMAT (*0*,*NOSE TIRES                   MAIN TIRES *)
      PRINT 139,RBPN1,RBPM1
139   FORMAT (* *,1X,F8.2,16X,F8.2)
      PRINT 8
8     FORMAT (*-*,*AIRCRAFT BRAKED DRAG RATIO, (R/P)E*)
      PRINT 7
7     FORMAT (* *,*-------------------------*)
```

```
      PRINT 180,S
180   FORMAT (* *,*FOR S=*,F4.0)
      PRINT9
9     FORMAT (*0*,*NOSE TIRES                     MAIN TIRES *)
      PRINT 70,RBPN,RBPM
70    FORMAT (* *,2X,F5.3,18X,F5.3)
      RN=0.564*SQRT(A1)
      Z=SN/RN
      Z1=71.7861+(51.055*Z)-(25.7398*Z**2)+(1.96582*Z**3)
      Z2=0.112318*Z**4
      FN=(Z1+Z2)/100
      ESWLN=SWLN1+(SWLN1*FN)
      RN2=0.564*SQRT(A2)
      W=SNM/RN2
      IF(W.LT.1.) GO TO 75
      W1=71.7861+(51.055*W)-(25.7398*W**2)+(1.96582*W**3)+(0.112318*W
     1**4)
      FM=W1/100
75    WA=SM/RN2
      IF(WA.LT.1.) GO TO 90
      IF (WA.GT.5.3) GO TO 90
      W1A=71.7861 + (51.055*WA)-(25.7398*WA**2)+(1.96582*WA**3)+(.112
     1318*WA**4)
      FM1=W1A/100
      IF(W.LT.1.) GO TO 90
      W2=(SQRT(SM**2+SNM**2))/RN2
      IF (W2.GT.5.3) GO TO 95
      W2A=71.7861 + (51.055*W2)-(25.7398*W2**2)+(1.96582*W2**3)+(.112
     1318*W2**4)
      FM2=W2A/100
90    FM1=0
95    FM2=0
      FMT=FM+FM1+FM2
      ESWLM=SWLM+(SWLM*FMT)
      CP=SWLN1/A1
      ESWL=ESWLN/1000
      CALL CBR(A,CP,ESWL,CBR1)
      CN=(6/CBR1)**6
      WN=0.874*SQRT(A1)
      PCN=(SN+80+WN)/(0.75*NN*WN)
      CP=SWLM/A2
      ESWL=ESWLM/1000
      CALL CBR(A,CP,ESWL,CBR1)
      CM=(6/CBR1)**6
      WM=0.874*SQRT(A2)
      PCM=(B1+80+WM)/(0.75*N1*WM)
      PN=CN*PCN
      PM=CM*PCM
      X=E-WM-B1
      YA=(E-WM-WN-B1-SN)/2
      IF (X.LT.80) GO TO 10
      H=80
      GO TO 11
10    H=X
11    IF (YA.LT.80) GO TO 20
```

```
      K1=80.
      GO TO 21
20    K1=YA
21    APN=(80*PN*PM)/(80*PM+(80-H)*PN+(80-K1)*PN)
      APM=(80*PN*PM)/(80*PN+(80-H)*PN+(80-K1)*PM)
      PRINT30
30    FORMAT (*-*,*NUMBER OF AIRCRAFT PASSES*)
      PRINT 32
32    FORMAT (* *,*--------------------------*)
      PRINT 35
35    FORMAT (*0*,*NOSE TIRES                      MAIN TIRES  *)
      PRINT 37,APN,APM
37    FORMAT (* *,3X,F4.0,21X,F4.0)
      IF (APN.LT.APM) GO TO 150
      T1=APM
      GO TO 155
150   T1=APN
155   PRINT 160,T1
160   FORMAT (*-*,*ALLOWABLE NUMBER OF AIRCRAFT PASSES =*,F4.0)
      PRINT 502, SWLN,SWLN1
502   FORMAT(*1*,*SWLN =*,F16.3,10X,*SWLN1 =*,F16.3)
      PRINT 504,D1,L1,A1
504   FORMAT(*-*,*DEFLECTION-NOSE =*,F16.3,10X,*PRINT LENGTH-NOSE =*,
     1F16.3,10X,*CONTACT AREA-NOSE =*,F16.3)
      PRINT 506, SWLM
506   FORMAT(*-*,*SWLM =*,F16.3)
      PRINT 508, D2,L2,A2
508   FORMAT(*-*,*DEFLECTION-MAIN =*,F16.3,10X,*PRINT LENGTH-MAIN =*,
     1F16.3,10X,*CONTACT AREA-MAIN =*,F16.3)
      PRINT 510,MM1,MM2
510   FORMAT(*-*,*DRAG MODIFIER-NOSE =*,F16.3,10X,*DRAG MODIFIER-MAIN =*
     1,F16.3)
      PRINT 512,ESWLN,ESWLM
512   FORMAT(*-*,*ESWLN =*,F16.3,10X,*ESWLM =*,F16.3)
      PRINT 514,CN,CM
514   FORMAT(*-*,*COVERAGES-NOSE =*,F16.3,10X,*COVERAGES-MAIN =*,F16.3)
      PRINT 516,PN,PM
516   FORMAT(*-*,*PASSES-NOSE =*,F16.3,10X,*PASSES-MAIN =*,F16.3)
600   CONTINUE
      END
```

```
      SUBROUTINE CBR(A,CP,ESWL,CBR1)
      REAL A(17,12)
      DO 40 I=2,17
      L1=A(I,1)
      IF (CP.GT.L1) N=I
      IF (CP.GT.L1) GO TO 45
40    CONTINUE
45    DO 50 J=2,12
      J1=A(1,J)
      IF (ESWL.LT.J1) K=J-1
      IF (ESWL.LT.J1) GO TO 55
50    CONTINUE
55    YN=(CP-A(N,1))/(A(N-1,1)-A(N,1))
      Y1=((A(N-1,K)-A(N,K))*YN)+A(N,K)
      Y2=((A(N-1,K+1)-A(N,K+1))*YN)+A(N,K+1)
      CBR1=((Y1-Y2)*((A(1,K+1)-ESWL)/(A(1,K+1)-A(1,K))))+Y2
      RETURN
      END
```

THE FOLLOWING IS A SAMPLE OF INPUT DATA FOR THE PROGRAM

```
$DATA

1
100000.  35.    35.    25.
33.4     18.    9.7    2.     38.5    18.5    12.75
3        3
8        4      4      1
235.     250.   275.   25.    80.     140.    25.5    20.    25.5    70.

$EOF
```

## SOLUTION TO TYPICAL DESIGN EXAMPLE OF SECTION IV

```
SINGLE WHEEL ROLLING DRAG, LBS.
-------------------------

NOSE TIRES                   MAIN TIRES
  310.63                      1100.36

SINGLE WHEEL ROLLING DRAG RATIO, (R/P)S
-------------------------------

NOSE TIRES                   MAIN TIRES
   .068                        .097

MULTI-WHEEL DRAG RATIO, (R/P)M
----------------------

NOSE TIRES                   MAIN TIRES              AIRCRAFT
   .059                        .080                   .078

MULTI-WHEEL DRAG, LBS.
----------------

NOSE TIRES                   MAIN TIRES              AIRCRAFT
  535.61                      7308.87                 7844.48

AIRCRAFT BRAKED DRAG, LBS.
--------------------
FOR S= 25.

NOSE TIRES                   MAIN TIRES
  3067.20                     6767.27

AIRCRAFT BRAKED DRAG RATIO, (R/P)B
--------------------------
FOR S= 25.

NOSE TIRES                   MAIN TIRES
   .675                        .596

NUMBER OF AIRCRAFT PASSES
-------------------------

NOSE TIRES                   MAIN TIRES
    43.                          71.

ALLOWABLE NUMBER OF AIRCRAFT PASSES = 43.
```

## 6. List of Symbols

| | |
|---|---|
| ACRPM | Multiwheel rolling drag for main tires |
| ACRPN | Multiwheel rolling drag for nose tires |
| ACRPT | Total multiwheel aircraft rolling drag |
| APM | Number of aircraft passes for main tires |
| APN | Number of aircraft passes for nose tires |
| BM | Section width of main tires (b) |
| BN | Section width of nose tires (b) |
| B1 | Distance from center of gravity of outer tire to center of gravity of inner tire - main and landing gear (B) |
| CBR1 | California Bearing Ratio (CBR1) |
| CPM | Main tire contact pressure (CP) |
| CPN | Nose tire contact pressure (CP) |
| DE | Deflection of nose tires ($\delta$) |
| DEM | Deflection of main tires ($\delta$) |
| DFM | Rim diameter of main tires (DF) |
| DFN | Rim diameter of nose tires (DF) |
| DM | Diameter of main tires (D) |
| DN | Diameter of nose tires (D) |
| E | Distance from center of gravity of one main gear to center of gravity of the other main gear (E) |
| ESWLM | Equivalent single wheel load for main tires |
| ESWLN | Equivalent single wheel load for nose tires |
| F | Distance from center of gravity of nose gear to center of gravity of main gear (F) |

| | |
|---|---|
| GW | Gross weight of aircraft (GW) |
| L | Distance from center of gravity of nose gear to center of gravity F.W.D. (L) |
| LL | Distance from center of gravity of nose gear to center of gravity A.F.T. (L') |
| M | Distance from center of gravity of main gear to center of gravity F.W.D. (M) |
| NM | Number of main tires (NM') |
| NM1 | Number of tires that are in a tandem-tracking situation - main gear |
| NN | Number of tires - nose gear (NN) |
| NN1 | Number of tires that are in a twin situation - main gear |
| N1 | Number of tires per main landing gear (N) |
| PCM | Passes per coverage main gear |
| PCN | Passes per coverage nose gear |
| RBPM | Braked drag ratio - main gear |
| RBPM1 | Braked drag - main |
| RBPN | Braked drag ratio - nose gear |
| RBPN1 | Braked drag - nose |
| RPM | Multiwheel drag ratio - main gear |
| RPN | Multiwheel drag ratio - nose gear |
| RPT | Aircraft multiwheel drag ratio |
| RPSM | Single wheel rolling drag ratio - main gear |
| RPSN | Single wheel rolling drag ratio - nose gear |
| RPSM1 | Single wheel rolling drag - main gear |

| | |
|---|---|
| RPSN1 | Single wheel rolling drag - nose gear |
| S | Percentage of tire slip (S) |
| SM | Spacing of twin tires - main gear ($S_M$) |
| SN | Spacing of nose tires ($S_N$) |
| SNM | Spacing of tandem-tracking tires - main gear ($S_N$) |
| SWLM | Single wheel load - main gear |
| SWLN | Single wheel load - nose gear |
| SWLN1 | Operational single wheel load - nose gear |
| TM | Tire type of main tires |
| TN | Tire type of nose tires |
| U | Distance from ground level to center of gravity FWD (J) |

# REFERENCES

1. Kraft, D. C., and Hoppenjans, J. R., "Design Procedure for Establishing Aircraft Capability to Operate on Soil Surfaces," AFFDL-TM-71-09-FEM, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, August 1971.

2. Kraft, D. C., "Analytical Landing Gear-Soils Interaction - Phase I," AFFDL-TR-68-88, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, August 1968.

3. Kraft, D. C., Luming, H., and Hoppenjans, J. R., "Aircraft Landing Gear-Soils Interaction and Flotation Criteria, Phase II," AFFDL-TR-69-76, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, November 1969.

4. Kraft, D. C., Luming, H., and Hoppenjans, J. R., "Multiwheel Landing Gear-Soils Interaction and Flotation Criteria, Phase III, Part I," AFFDL-TR-71-12, Part 1, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, May 1971.

5. Gray, D. H., and Williams, D. E., "Evaluation of Aircraft Landing Gear Ground Flotation Characteristics for Operation from Unsurfaced Soil Airfields," AFFDL-TR-68-34, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, September 1968.

6. Air Force Systems Command Design Handbook, AFSC DH2-1, Airframe, April 7, 1969.

7. Kraft, D. C., Luming, H., Hoppenjans, J. R., and Bogner, F., "Multiwheel Landing Gear-Soils Interaction and Flotation Criteria - Phase III, Part II," AFFDL-TR-71-12, Part II, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, January 1972.

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13. ABSTRACT

This report summarizes a systematic design procedure for establishing various landing gear combinations of tire sizes, spacings, and configurations which will minimize rolling drag and satisfy the criteria of 200 nonbraking passes of a selected STOL aircraft operating on a standardized CBR6 (or equivalent) soil surface. The design procedure presented herein combined the latest results of Air Force sponsored landing gear/soil interaction research with the previously developed WES coverage techniques.

This procedure is a first attempt to make the research results of existing Air Force Flight Dynamics Laboratory programs available toward the improvement of flotation design capability. This design procedure, subject to certain stated limitations, includes techniques for (1) predicting rolling and braking drags and drag ratios, (2) incorporating multiwheel influences on drag and sinkage, and (3) determining aircraft passes. Additionally, the design procedure has been incorporated in a computer program format for utilization on the CDC 6600 located at Wright-Patterson Air Force Base. The computer program is restricted at present to aircraft with tricycle type landing gear systems.

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