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EVALUATION OF CONTINGENCY SURFACES FOR LOW VOLUME AIRCRAFT TRAFFIC, PHASE I

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There is a need, when contingencies so dictate, for US Air Force, Base Civil Engineers (BCE) to have the capability of making use of unusual or irregular surfaces for support of low volumes of aircraft traffic. Much information exists in guide manuals and in reported research, which is applicable to evaluation of such surfaces for their capability to support aircraft traffic. There is, however, no single document available to the BCE which provides guidance in the evaluation of surfaces for such use in a contingency.

This study undertakes development of a procedures manual for BCE to provide guidance in testing and evaluation of surfaces for support of ground operations of aircraft. Use, in a contingency, by USAF inventory aircraft for limited operations is contemplated, and virtually any suitable type surface, from unprepared soil to conventional paving, is included.

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19. ABSTRACT (Continued).

The Phase I effort examines needed guidance to be included, surveys the technology contributing to satisfaction of these needs, and presents guidance to established methodology and source material for use in development of the planned manual.

Short-term needs which can and should be satisfied for incorporation in the manual are listed. Long-term needs identified for future study are also delineated.

PREFACE

This report was prepared by Civil Engineering Consultant, Richard G. Ahlvin under Waterways Experiment Station Contract No. DACA 39-87-M-0659. Guidance and casual support were provided by the Pavement Systems Division, Geotechnical Laboratory, of the US Army Engineer Waterways Experiment Station. The study was conducted for the Pavement Technology Branch, Engineering and Services Center, Department of the Air Force, Tyndall Air Force Base, Florida. The reported work was carried out between June and December 1987.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. BACKGROUND

There is a need for the United States Air Force (USAF), Base Civil Engineers (BCE) to have the capability of making contingency use of unusual or irregular surfaces for support of low volumes of aircraft traffic. Much information exists in guide manuals as well as applicable reported research to evaluate the capability of such surfaces to support aircraft traffic. There is, however, no single document available to the BCE which provides guidance in the evaluation of surfaces for contingency use. It is thus desirable to develop such a document, prepared for BCE staff use, without a requirement for support of a highly trained pavement engineer.

B. PURPOSE

The objective of this study is to produce a procedures manual for BCE to provide guidance in testing and evaluation of surfaces for the support of ground operations of aircraft. Use, in a contingency, by USAF inventory aircraft for limited operations is contemplated, and virtually any suitable type surface, from unprepared soil to conventional paving, is to be included.

C. SCOPE OF PHASE I

The first phase effort is to examine the needed guidance to be included in the BCE manual and to survey the technology contributing to satisfying these needs. Elements of this survey will be reported, and additional work required to satisfy deficiencies in the existing technology will be delineated and reported. An outline of the proposed manual will be prepared.

D. SCOPE OF THE BCE CONCERNS

Considering circumstances which might create the need for contingency use of surfaces not normally intended for such use, it appears that a military or terrorist action might deny use of regular operating surfaces. Regular facilities might be disrupted or blocked by storm or earthquake destruction or by a severe aircraft accident. A buildup of traffic to support a contemplated military response, to combat a natural disaster in the vicinity, or merely to support a large military exercise might require parking and access surfaces beyond those existing.

For contingency use the BCE may need to evaluate conventional pavements not regularly intended to sustain mission aircraft for their ultimate capacity to support from a few to a number of heavy aircraft passes. Conventional pavement types would include flexible, rigid, overlay, and aggregate surfaced, and actual pavements might include secondary runways, taxiways, or apron areas not intended for use by mission or heavy aircraft, abandoned or closed facilities which have not been maintained, shoulders and overruns of primary pavement facilities, connecting and access roads, and ground vehicle parking and open-storage areas.

The BCE may also need to evaluate unsurfaced soil areas for contingency traffic or aircraft parking. Infield areas and areas adjacent to runways, taxiways, or aprons may need to be crossed, used for parking, or to serve as alternate runways or taxiways. It thus becomes necessary for the BCE to have the capability of evaluating soil areas for common rolling, turning, braking, and stopping or parking. If take-off and landing on soil surfaces are required, the BCE must also assess roughness in relation to aircraft response and drag as it contributes to the length of take-off runs.

For each of the elements of BCE concern expressed for conventional or unsurfaced soil areas, the capability to evaluate must extend to support for any of the variety of USAF aircraft which might require support. It also needs to cover a repeated use range from a few to over a hundred passes.

E. MANUAL COVERAGE

The manual to be developed under the overall study and to be outlined as part of Phase I will need to address each aspect of conventional pavements, unsurfaced soil areas, aircraft, and traffic operations covered in Section D. It will also need to cover means of assessing the attributes of each type of landing surface such as the following: surface strength, both in relation to aircraft support and to increased drag, subgrade strength, structure thickness and assurance of adequate condition and quality of elements of the structure, direct evaluation of load support capacity, and wheel path profiles and roughness response.

SECTION II

BACKGROUND

A. AIR FORCE AIRCRAFT

Not all Air Force aircraft for functional or operational reasons have need of contingency surface support. Air Force engineer guidance has indicated helicopters, training aircraft, and surveillance aircraft need not be covered by this study. The statement of work for this project suggests a general grouping by type such as fighter, intratheater cargo, intertheater cargo, etc. Air Force engineer guidance suggests emphasis on fighter and cargo (both medium and heavy) types of aircraft. Air Force Magazine for 1987 (Reference 1) in its "Gallery of USAF Weapons" lists current USAF aircraft. Table 1 is a listing of these aircraft as they relate to this study. The Air Force aircraft group index, as shown in AFM 88-24, Chapter 1 (Reference 2) and included in most airfield evaluation reports, is as shown in Table 2. This is the current manual listing of Air Force aircraft intended to be covered by pavement evaluations. Characteristics for aircraft of concern were obtained primarily from the Air Force Engineering and Services Center (AFESC) report by Millard (Reference 3). In a few cases data were obtained from other, mostly older, similar compilations. Based on Air Force guidance and the sources indicated, the types of aircraft considered of concern and their loading characteristics were assembled. These aircraft are listed in Table 3.

B. APPLICABLE EVALUATION TECHNOLOGY

Airfield pavement technology and related military needs for limited use of conventional type pavements and alternate or expedient landing surfaces have enjoyed extensive past development. Thus, there is substantial existing or recently developed evaluation methodology which is applicable here.

1. Conventional Pavement

Pavement evaluation guidance for flexible, rigid, and overlay pavements at USAF installations are contained in a series of Army and Air Force manuals. These manuals are TM 5-827-1/AFM 88-24, Chapter 1 (Reference 2), TM 5-827-2/AFM 88-24, Chapter 2 (Reference 4), TM 5-827-3/AFM 88-24, Chapter 3 (Reference 5), and TM 5-330/AFM 88-3, Volume II (Reference 6). The guidance in these manuals is a digest of extensive development and experience verification. It thus provides a sound basis for evaluation of pavements for normal use by mission aircraft or for expedient theater-of-operations and equivalent usages. However, only limited verification of the criteria on which these evaluation methods are based have been accumulated to support their extrapolation down to the very low (0 to 100) repetition or pass levels contemplated for this study. The verification of low repetitions extrapolation is probably adequate for flexible pavements. For rigid pavements it is minimally acceptable. For overlay pavements, however, such extrapolation rests largely on engineering judgement, but the judgement is considered to be reasonably sound.

TABLE 1. CURRENT USAF AIRCRAFT (CONTINUED).

CODE	NAME/MANUFACTURER	TAKE-OFF WEIGHT, KIPS
	Bombers	
B-1 B	Rockwell International	477.0
B-52	Stratofortress/Boeing	488.0
FB-111A	General Dynamics	100.0
	Fighters	
F-4	Phantom II/McDonnell	61.8
F-5	Tiger II/Northrup	24.7
F-15	Eagle/McDonnell	68.0
F-16	Fighting Falcon/General Dyanmics	37.5
F-106	Delta Dart/Convair (Gen. Dyn.)	42.4
F-111	General Dynamics	47.5
	Attack and Observation	
A-7	Corsair II/LTV Aerospace	42.0
A-10	Thunderbolt II/Fairchild Republic	50.0
CA-37B	Dragonfly/Cessna	14.0
OV-10A	Bronco/Rockwell International	14.4
	Reconnaissance and Special Duty	
EF-111A	Raven/Grumman	88.9
E-3	Sentry (AWACS)/Boeing (707)	325.0
E-4B	Boeing (747)	800.0
	Transports and Tankers	
C-5	Galaxy/Lockheed	837.0
C-9A	Nightingale/Douglas (DC-9)	108.0
C-12	Huron/Beech	12.5
C-20	Gulfstream III/Gulfstream Aerospace	69.7
C-17	Heavy-Lift Cargo/Douglas Aircraft	370.0
C-21A	Gates Learjet (35A)	18.5

TABLE 1. CURRENT USAF AIRCRAFT (CONCLUDED).

CODE	NAME/MANUFACTURER	TAKE-OFF WEIGHT, KIPS
	<u>Transports and Tankers (Continued)</u>	
C-22B	Boeing (727)	170.0
C-23	Sherpa/Short Brothers PLC	22.9
VC-25A	Boeing (727)	814.0
C-130	Hercules/Lockheed	175.0
C-131	Samaritan/Convair (C-131)	63.0
KC-135	Stratotanker/Boeing	297.0
C-135	Stratolifter/Boeing	275.5
C-137B/C	Stratoliner/Boeing (707)	258.0/322.0
C-140	Jetstar/Lockheed	40.9
C-141	Starlifter/Lockheed	343.0
KC-10	Extender/Douglas	590.0

TABLE 2. AIR FORCE AIRCRAFT GROUP INDEX

1	2	3	4	5	6	7	8	9	10	11	12	13
C-123[a]	F-15[a]	F-111[a]	C-130[a]	C-9[a]	T-43[a]	B-727[a]	E-3[a]	C-141[a]	C-5[a]	KC-10[a]	E-4[a]	B-52[a]
	A-7			C-7	737	KC-97	707	B-1		DC-10	747	
	A-10			DC-9	C-119		C-135			L-1011		
	A-37			C-54	EC-121		KC-135			C-17		
	F-4			C-131			VC-137					
	F-5			C-140								
	F-14			T-29								
	F-16											
	F-100											
	F-101											
	F-102											
	F-105											
	F-106											
	T-33											
	T-38											
	T-39											

[a] Controlling aircraft.

TABLE 3. CONTINGENCY SURFACES STUDY, AIR FORCE AIRCRAFT (CONTINUED).

AIR FORCE GROUP	AIRCRAFT	WHEEL LOAD (KIPS)	CONTACT PRESSURE PSI	GEAR TYPE	SPACING, IN. TWIN	SPACING, IN. TANDEM	NOTES
1	C-123	25.3	92	Single	--	--	--
2	F-15	22.1	260	Single	--	--	--
2	A-7	17.5	280	Single	--	--	--
2	A-10	22.9	185	Single	--	--	--
2	A-37	6.3	100	Single	--	--	--
2	F-4	25.4	265	Single	--	--	--
2	F-5	9.5	318	Single	--	--	--
2	F-16	15.0	275	Single	--	--	--
2	F-106	18.1	287	Single	--	--	--
3	F-111	45.0	180 (nose 280)	Single	--	--	--
4	C-130	41.9	105	Single-tandem	--	60	--
5	C-9 (DC-9)	25.8	148	Twin	25	--	--
5	C-131	14.7	90	Twin	26	--	--
5	C-140	8.8	205	Twin			
6	T-43 (737)	26.8	148	Twin	30.5	--	--
6	C-119	17.5	80	Twin	28.3	--	--
6	C-121	34.6	130	Twin	33	--	--
7	B-727	40.0	168	Twin	34	--	--
7	KC-97	44.5	180	Twin	37	--	--
8	E-3 (707)	37.3	190	Twin-Tandem	34	56	--

TABLE 3. CONTINGENCY SURFACES STUDY, AIR FORCE AIRCRAFT (CONCLUDED).

AIR FORCE GROUP	AIRCRAFT	WHEEL LOAD (KIPS)	CONTACT PRESSURE PSI	GEAR TYPE	SPACING, IN. TWIN	SPACING, IN. TANDEM	NOTES
8	KC-135	37.3	155	Twin-Tandem	36	60	--
8	C-137	39.3	190	Twin-Tandem	34	56	--
9	C-141	41.0	196	Twin-Tandem	32.5	48	--
9	B-1	53.6	262	Twin-Tandem	40	54	--
10	C-5	32.9	115	Dual delta twins	34-53-34 front 48-rear Front assembly 30-33-30	65	220 in. front to rear assembly 310 in. left to right assembly
11	KC-10 (DC-10)	57.5	185	Twin-tandem (twin belly)	54	64	--
11	L-1011	50.7	180	Twin-tandem	52	70	--
11	C-17	44.0	120	Trip-tandem	42.5-40.5	97	--
12	E-4 (747)	44.5	200	Twin-tandem (double)	44	58	121 front to rear 142-150-142 left to right
13	B-52	67.0	305	Twin-twin (bicycle)	37-62-37		--

2. Earth Surfaces for Aircraft Support

Guidance for evaluation of earth landing and operating surfaces for support of aircraft has received significant study and development. Early work in relation to airfield landing mat and membrane surfacing behavior (Reference 7) involved tests on unsurfaced soil areas using 10 to 50 thousand pound wheel loads and 50 to 150 psi tire pressure single-wheel loads. The resulting aircraft support criteria gained validation from field tests with the C-123 and C-130 aircraft (Reference 8).

a. Extensive Initial Corps-of-Engineers Studies

Operational studies of roughness and drag using the C-130 aircraft on unsurfaced strips provided further verification (References 9, 10, and 11) and led to published criteria (Reference 12). The extensive "ground-flotation" investigation which followed this, anticipating development of the C-5 aircraft, provided further verification and extension of the criteria to multiple-wheel aircraft (Reference 13). Criteria for aircraft ground flotation were published (References 14 and 15), which are still the latest Corps of Engineers unsurfaced soil criteria. Figure 1 shows these criteria, using airfield index for the soil strength parameter in the form commonly referred to as the "unsurfaced nomograph." The specific aircraft type curves in Appendix D of AFM 86-3, Volume II (Reference 6) are based on these unsurfaced strength relations instead of the latest version of the nomograph curves. Figure 2 is the latest equivalent single-wheel load-adjustment curve for unsurfaced soils which permits application of the unsurfaced soil criteria to multiple-wheel load aircraft.

b. Bare Base Studies

The bare base support studies permitted further validation of the nomograph criteria, with special reference to F-4C type aircraft and permitted study of the behavior of fighter type aircraft when braking on unsurfaced soils (Reference 16). These confirmed applicability of the nomograph curves for free rolling on soils in general and braking on cohesive soils, but braking on soils with little or no cohesion requires much greater strengths than those of the nomograph to control rutting.

c. C-5 and C-144 Testing

Further verification of the unsurfaced soil support criteria has been provided by the C-5 (References 17, 18, and 19) and C-141 (Reference 20) aircraft testing on bare soil surfaces.

d. Applicable Mobility Research Findings

Applicable to the problem of aircraft operating on earth surfaces is the technology that began over 30 years ago, and now characterized as "off-the-road mobility of terrain-vehicle systems." This is the technology which examines the capability of ground vehicles to traverse soft soils. Early emphasis on good flotation ground vehicles crossing very soft soils and lack of emphasis on good ground flotation of aircraft using earth surfaces left the two concerns as largely separate problems. With trends in both, however, the

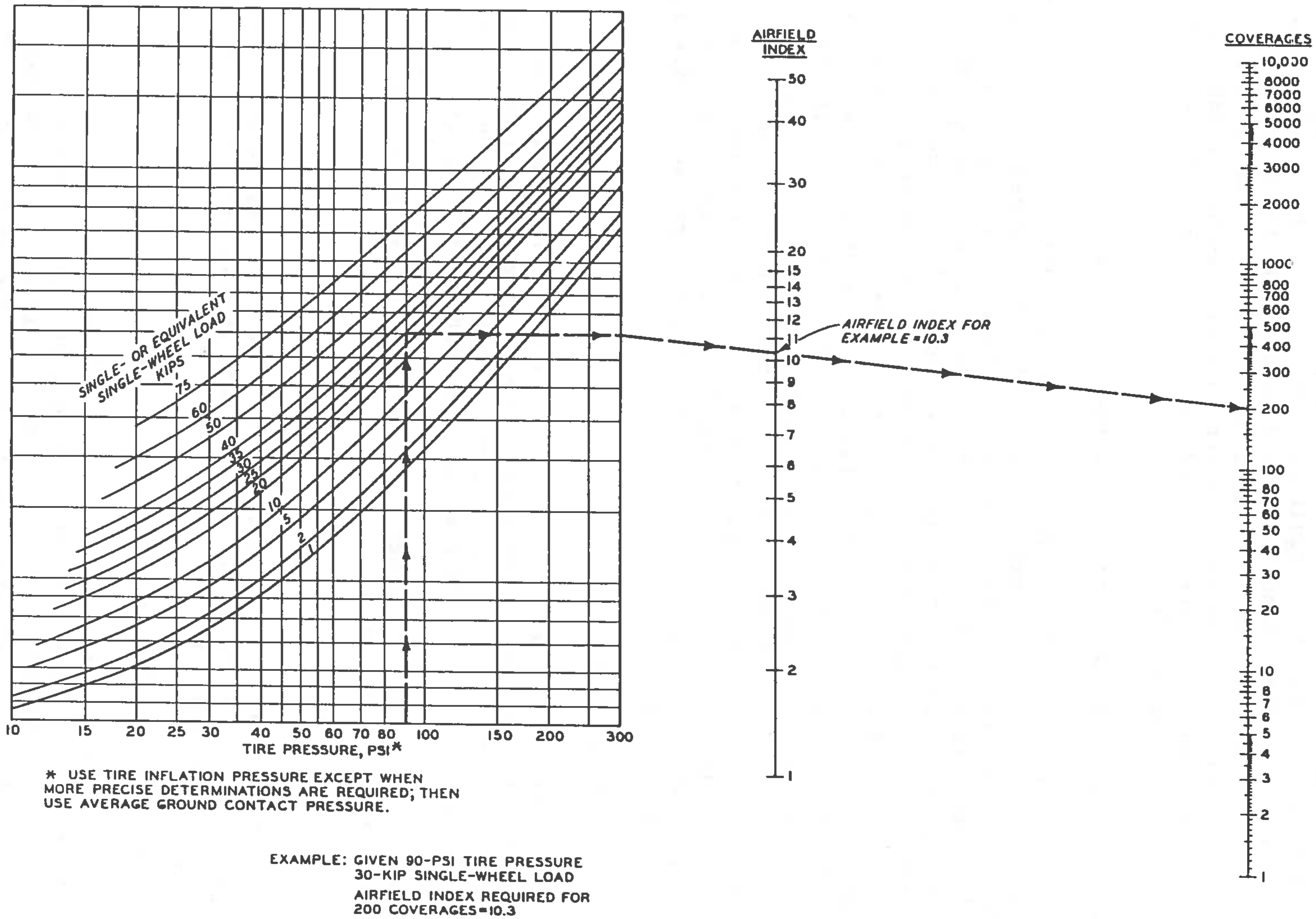
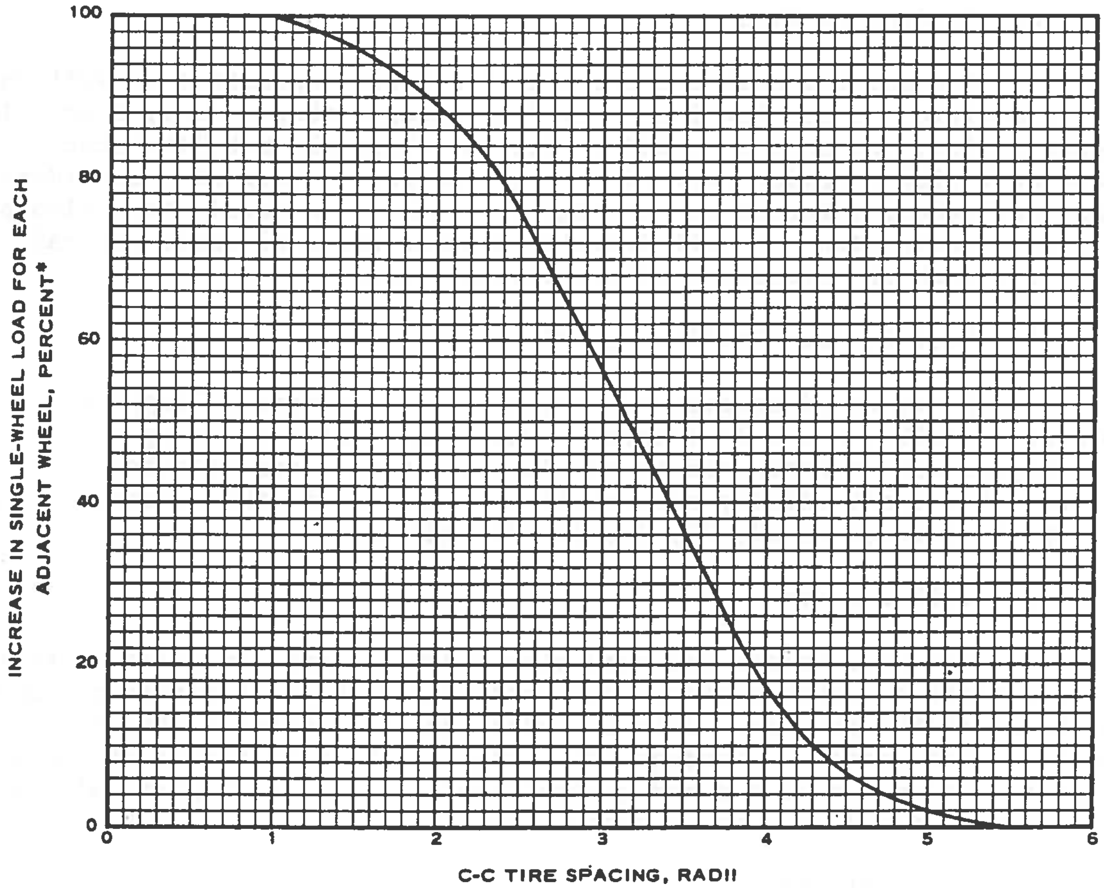


Figure 1. Airfield Index Required for Operation of Aircraft on Unsurfaced Soils.



* 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.

Figure 2. Equivalent Single-Wheel Load-Adjustment Curve for Unsurfaced Soils.

technologies have come together so that the load/sinkage and drag information developed for ground vehicles have contributed to studies of aircraft on soil surfaces. A thesis work by Wang (Reference 21) some 10 years ago attempted to examine comprehensively the ground mobility technology and provide applications to aircraft operations. The thesis includes a good treatment of historical development and an excellent bibliography.

e. Studies by Wang

Recognizing that the problem of aircraft operation on soil surfaces in addition to complex interrelations among sinkage, drag, load, tire characteristics, and soil type and conditions which the mobility studies address must also consider forward velocity effects. Wang also considered the dynamic soil/wheel interactions at higher speeds. His thesis thus also provides some examinations of soil dynamics studies and applicable aircraft field trials with back-up references in his thesis index.

f. Soil Surface Studies by AFFDL

A series of studies supported by the Air Force, Flight Dynamics Laboratory (AFFDL), Mechanical Branch, which were carried out by the University of Dayton also contributed to the data defining aircraft behavior on soil surfaces. Those not already referenced are included in the reference list for this report (References 22, 23, 24, 25, 26, and 27).

g. SAFE Studies

The more recent and predominant developments in relation to aircraft operation on earth surfaces were made under the soil airfield fighter environment (SAFE) program. This includes some 21 reports listed in the References (References 28 through 48). Because the most recent of these 21 reports includes selected and generalized information of particular use it is also separately listed in Reference (49).

3. Layered Earth Surfaces

Soil surfaces for support of aircraft can be layered. Erosion outwash can place weaker soil over firmer soil or limited rainfall can result in a weaker surfacing layer. Conversely, drying can lead to a "crust-like" surfacing or evaporation in arid regions can result in a natural chemical stabilization of the surface layer. Commonly, it is accepted that the root-mat from plant growth provides a stronger surface. In the case of a root-mat or sod surface some very limited tests at the US Army Engineer Waterways Experiment Station many years ago (Reference 50), showed that the root-mat for low plant growth provides only very limited added support and for only two or three vehicle passes. The SAFE Program summarizing work (Reference 49) presents some detail of the layered soil study in its Appendix C. It is based on finite element model theoretical studies (Reference 51). The resulting guidance is shown in Figure 3.

Surfacing	Common Rolling	Turning	Braking	Parking or Stopping	Roughness	Drag
Bare Soil	A	N	N	N	P	N
Layered Soils	N	X	X	X	X	P
Aggregate Top Layer	N	X	X	X	N	X
Flexible Pavement	A	X	X	X	A	X
Rigid or Overlay Pavement	N	X	X	X	A	X
Weak Top Structure Pavements	P	X	X	P	U	U
Landing Mat	N	X	N	X	P	P

A - Adequate basis for criteria formulation.
N - Nominal or partially adequate basis for cirteria formulation
P - Poor but usable basis for criteria formulation.
U - Unsatisfactory or no basis for criteria formulation.
X - Extraneous, not applicable, or not separately needed.

Figure 3. Matrix of Response Criteria Needed for Contingency Surfaces for Low Volume Aircraft Traffic.

4. Aggregate Surfaced Aircraft Operating Areas

Criteria have been developed for evaluating the thickness of aggregate surfacing in relation to subgrade strength and load support capability (References 51 and 53). These are applicable to unsurfaced (no hard surfacing such as asphalt or concrete) roads and airfields. Two somewhat different analyses of the same performance data have been published. One of these (Reference 54) produced the following relation for use in pavement evaluation (or design).

$$t = (0.176 \log C + 0.120)\sqrt{\frac{P}{8.1\ (CBR)} - \frac{A}{\pi}}$$

where
- t = thickness of aggregate layer in inches
- C = coverages (to failure)
- P = single or equivalent-single wheel load
- A = contact area of the single wheel

This obviously strongly follows the pattern of conventional CBR design for flexible pavements but yields smaller thicknesses consistent with allowing some degree of surface disruption or rutting. The second analysis of the same basic performance data is a thesis by Hammitt (Reference 53). This analysis presents the following relation for evaluation:

$$t = \frac{P^{0.215} \cdot p^{0.626} \cdot C^{0.239}}{10.5 \cdot \overline{CBR}_s^{\,0.403} \cdot \overline{CBR}_c^{\,0.314}}$$

where
- t = thickness in inches
- P = single or equivalent single-wheel load
- p = tire pressure or average tire contact pressure
- C = coverages (to failure)
- $\overline{CBR}_s$ = subgrade (CBR) strength
- $\overline{CBR}_c$ = cover layer (CBR) strength

This analysis differs from the other in providing for an element of the total thickness required based on the CBR (strength) of the cover layer. Some further applicable performance data providing further verification of these analyses were provided by C-5A testing on unsurfaced soil surfaces (Reference 51). Note that the analysis under "Layered Earth Surfaces" in the previous section, insofar as it relates to a firm layer over a weaker layer, is similar to the analyses in this section for thickness of strengthening (aggregate) layer over a subgrade. Some intercomparison of these three offered bases for evaluation of thickness of top (strengthening) layer, over a softer (subgrade) layer, and resolution of any differences is indicated.

5. Expedient Surfaces for Rapid Airfield Construction

Membranes and landing mats have been developed for use as rapidly emplaced airfield surfacings. Mat and membrane development literature is too extensive for delineation in this paper, but Army and Air Force manual, TM 5-330/AFM 88-3, Volume (Reference 6), attempts to sufficiently cover types and applications. Since the interest in contingency surfaces extends to only a relatively small number (100 or so) of aircraft passes, and because membranes do not contribute to structural strength, but only preserve existing strength of unsurfaced areas, the applications of membranes to contingency surfaces will be minimal. They will thus not be discussed in this paper beyond the guidance in AFM 88-3, Volume II. Landing mats do provide substantial structure when placed over soft soil to serve as taxiways, parking aprons, runways, or repairs or extensions to runways (Reference 55). Rarely will mat operating surfaces be in place at airfields to be evaluated for contingency use. Thus, mat applications will involve design and installation. Some of the same studies which provided design and evaluation criteria for unsurfaced facilities also involved behavior of landing mat (References 7, 13, and 20). The basis devised for providing design (or evaluation) criteria for any particular loading on landing mat has been documented (References 56, 57, 58, and 59), and manual AFM 88-3, Volume II (Reference 6) contains specific criteria for some fighter type and some transport type aircraft.

SECTION III

ELEMENTS OF CONCERN

A. OPERATIONS REQUIRED

Contingency surfaces may be required for taxiing, parking, or take-off and landing.

B. OPERATING AREAS

Contingency operations may be necessary on existing pavements not intended to support the aircraft contemplated by the impacting contingency. This might include heavy aircraft on light-duty airfields, fighters or transports on training bases or auxiliary fields, mission aircraft on secondary facilities not intended for their use, and even to roadways, parking areas, or other pavements not intended for aircraft use. Old pavements not regularly maintained or abandoned pavements returned to service may need evaluation for contingency use. Earth surfaces will need assessment for support of taxi operations, parking, or runway. Gravel or aggregate surfaced areas will need to be evaluated. These may be existing facilities diverted to contingency use or may be constructed surfaces designed to support the contingency operations. Few, if any, expedient surfaced (landing mat or membrane) facilities are in place at Air Force bases. Any which do exist and are to be considered for contingency use must be evaluated. The more common application of expedient surfacings will be in strengthening earth surfaces that are too weak or maintaining the (dry) strength of soil surfaces which would become too weak when wetted by rainfall. Landing mats can be placed to provide structure strength. Membranes only retain existing strength and help control dust.

C. FUNCTIONAL ASPECTS

Characteristics of the using aircraft determine or limit operating surface characteristics for any, including contingency, ground operations.

1. Pavement Structure Determining Aircraft Characteristics

The structure requirements of an operating surface for support of aircraft is determined by the magnitude and distribution of loading on the surface. Of first concern is the magnitude of individual tire loads, but the combining effects of closely spaced loads of multiple-wheel landing gear must be considered, particularly where load-distributing upper layers of structure are involved. Commonly, this combined effect of two or more tire loads is treated as an equivalent single-wheel load (ESWL) for design and evaluation purposes. The ESWL, however, is not a single value loading, but varies as a function of the depth to a critical layer of the structure, i.e., less combining at shallow depth and more at deeper depth. Tire or tire-contact pressure is also a factor and can be the predominant concern in relation to support of loading by surfaces where the upper layer is critical, i.e., earth surfaces or weak bases with only thin or severely cracked surfacing.

2. Aircraft Characteristics Influencing Operational Response of Support Surfaces

Aircraft response to roughness is a factor limiting the configuration of supporting surfaces and to some degree the character of deformable (rutting) earth or other very weak surfaces. This is especially true where high speed operations are necessary but can impact at relatively slow speeds in some cases. Ground clearance can limit the tolerable surface disruption (rutting) for individual aircraft. Thrust available to overcome drag, which is attendant to rutting and surface distortion can be a limiting parameter for support surfaces. This can also increase the length of take-off strips required.

D. TRAFFIC CONCERNS FOR CONTINGENCY OPERATIONS

The use of contingency surfaces will involve only low numbers of passes or repetitions of load. The BCE will doubtless need to know whether one to a few passes can be completed with reasonable certainty. Beyond this the BCE may wish to know that perhaps up to 100 passes can be supported. Contingency use is not likely to require more passes, and experience with the initial traffic will suggest any needed reworking or upgrading to permit continued contingency operations.

Least demands of severe loadings on contingency operating surfaces will result from simple rolling of aircraft with only very mild turning and braking. More severe maneuvering and braking will require stronger operating surfaces. Parking or stopping for significant time in one location can in extreme circumstances permit the settlement of aircraft wheels and development of surface depressions. Greater power is required to move from such depressions than for rolling without stopping. Since aircraft have limited power, the surface which can support stopping must be stronger than required for support of simple rolling.

E. MATRIX OF RESPONSE CRITERIA NEEDED

A matrix has been formulated relating the various types of surfacing, each requiring separate technology, to the various factors limiting operations using each surface type. Figure 3 shows this matrix. It includes coding of the applicable technology supporting each matrix element. Although the coding is explained in the figure, each element will be explained in a later section.

SECTION IV

ELEMENTS OF DEFINITIVE CRITERIA

A. SUBGRADE STRENGTH

A primary element of any pavement structure is the soil or subgrade on which the structure rests. This is true whether the structure is conventional asphalt or concrete with bases and subbases as pertinent, aggregate (gravel), stabilized top layer, or landing mat surfaced. Some measure of strength or response to load is needed for pavement design or load support evaluation, either directly measured or indirectly determined. A variety of conventional and rapid expedient means for evaluating subgrade strength has been devised.

Military methods for subgrade evaluation for conventional pavements can be found in Military Standard 621 (Reference 60). These are represented by the CBR (California Bearing Ratio) for asphalt (flexible) pavements. Concrete (rigid) pavements use the modulus of subgrade reaction k for rating subgrade strength, but commonly the modulus values required are evaluated using correlations with CBR or other equivalent measurements. Aggregate or landing mat surfaced operating areas also commonly use CBR or equivalent for evaluation.

The airfield cone penetrometer (Reference 61) was developed for rapid field measurement of "airfield index" (AI) as a representation of subgrade strength or of unsurfaced soil strength as discussed in the following section. The airfield penetrometer was derived from the trafficability penetrometer described in AFM 86-3, Volume II (Reference 6) which measures the "cone index" (CI) for assessing the strength of very soft soils for correlation with the trafficability or mobility of ground vehicles. Correlations of either AI or CI with CBR make the generally available design and evaluation criteria (References 2, 4, 6, 7, 14, 52, 53, and 56) which use CBR available for use with rapid strength assessment by penetrometer.

It should be recognized that for evaluation of subgrade strength beneath existing pavement structures, the layers above the subgrade must be removed or penetrated by coring, to permit either conventional tests (CBR or plate testing) or penetrometer use in the subgrade.

B. SOIL SURFACE STRENGTH

Operation directly on soil surfaces evaluation of load support capability depends directly on assessment of soil strength. The same tests used for subgrade strength determination apply to soil surfaces. For consistent, rapid, and easily recorded measurement of soil strength at the surface and to some depth, and assessing broad areas for operational use, the Air Force supported development of an automated penetrometer (Reference 62). The device can be vehicle mounted for rapid and extensive field use or mounted on a frame in the laboratory for correlation studies.

Other means of measuring soil strength in the field have been studied (References 63 and 64), but the penetrometer appears to offer the best rapid field assessment means. There is strong current interest in a drop-weight penetrometer which rates strength in terms of "blows-per-foot" or the equivalent. The blow count correlates well with CBR, and the cone can be driven through aggregate layers or other stiff top crusts. Several "drop-cones" or "dynamic penetrometers" have been devised using a variety of cones, drop-heights, and weights, but current interest by Air Force elements, studies at the US Army Engineer Waterways Experiment Station (WES), and others are in a device being used by the Israelis (Reference 65). There is active interest in the Clegg Hammer (Reference 64) for bare soil strength evaluation, but the penetrometer in some form appears to hold more promise. Boeing has developed a penetrometer (Reference 66) and correlations with CBR for soil surfaces and for aggregate layers.

C. PAVEMENT STRUCTURE

A pavement structure accepts the wheel loads on its surface and spreads the load, reducing its pressure to something the subgrade can sustain. The structure must be thick enough (surface to subgrade) to sufficiently distribute or spread the load and must be strong enough on (or near) the surface to sustain the pressure applied by the tires.

For evaluation thicknesses must be determined, except when some direct weight-bearing evaluation methods are used, which will be mentioned later. Thicknesses can be obtained from cores in test excavations or from suitable construction records.

Character and condition of surface and near-surface layers of the structure must be such as to support the tire pressure and, to a degree, the load applied. Structures planned for only low to moderate tire pressures are not likely to satisfactorily support high tire pressures. Surfaces and/or bases which have not been properly maintained may not support higher or even moderate tire pressures. Too thin structures in good condition may be broken and severely displaced by large contingency overloading.

Criteria for conventional pavement can be found in References 4, 5, and 6, for aggregate (gravel) surfaces in References 51 and 52, and for landing mat in References 56, 57, and 58.

D. LAYERED SOIL

The descriptions of operations directly on soil surfaces assume the soil will be reasonably uniform for some depth from the surface. There is a need also to consider layered soil in which there may be a stronger top layer or crust over a weaker subsoil or in which there may be a weaker or soft surface layer over a stronger subsoil. Means for treating the strength evaluation of layered soils were developed as part of the SAFE program (subitem 17 in Reference 28 and Appendix C of Reference 49).

Firmer layers over weaker subsoil are also treated by the criteria for aggregate (gravel) surface layers (References 53 and 54). Some closer comparisons of these two means for stronger overlayer evaluation need to be undertaken and any differences accommodated or resolved.

As earlier mentioned, there is commonly an acceptance that a sod (root-mat) surface helps support load. However, some limited tests at WES many years ago (Reference 50) showed that a sod surface is quickly deteriorated and contributes very little to load support.

E. DIRECT EVALUATION

In Part A of this section the elements of a pavement structure or soil surface which must be considered in relation to load support evaluation were discussed. Alternatively, there are means for direct evaluation of the load support capacity of operating surfaces. Because these methods do not require opening pits into the pavement structure to determine strengths and thicknesses of the structure layers, they are called nondestructive test (NDT) methods. An overview of a variety of such methods is included in Chapter 3 of the 1983 version of the International Civil Aviation Organization (ICAO), "Aerodrome Design Manual, Part 3, Pavements," Second Edition, 1983 (Reference 65).

NDT methods employing induced dynamic loadings have enjoyed intensive development and have been widely documented. Several references indicating current methods are found in TRB, Transportation Research Record 1022, "Analysis and Testing of Granular Bases and Subbases" (References 66, 67, and 68).

Means have been developed for direct evaluation of unsurfaced soil areas for support of aircraft based on observing the supporting response of ground vehicles on the operational area of interest (References 69 and 70).

SECTION V

MEANS OF TREATMENT

A. LOADING

Any evaluation, whether for contingency or commonly intended use, of an operating surface will have primary concern for the aircraft loading. The critical elements of loading are the magnitude of individual wheel (or tire) load, the interaction or combining effects of adjacent wheels, and the tire contact pressure. Each element must be considered and dealt with in any evaluation of a surface to support aircraft operations. Obviously, the ability of a particular surface or pavement to support an aircraft is greatly influenced by the magnitudes of the loading elements, but the methodology or criteria used to evaluate are not influenced by the magnitudes. Thus, a manual giving guidance to BCE in contingency use of operating surfaces will need to deal with aircraft loading, but loading will not variously impact on weak or inadequate elements of the applicable technology.

For best evaluations the individual aircraft, as listed in Table 1, might be dealt with directly, but the volume and complexity of such an approach argue for some means of collective treatment. The 13 groupings of Table 2 used for regular Air Force evaluations and the controlling aircraft for each group might be used, but these accept some generalizations of wheel interaction effects and do not provide well for tire pressure variation. For conventional pavements and those for which the subgrade strength is of most critical concern, the tire pressure is not especially sensitive. However, for soil surfaces or any pavement for which the surface strength is more critical than structure and subgrade strength, the tire pressure is the most significant element for evaluation. Use of the 13 groupings with a separate consideration of tire pressure, where pertinent, may be a viable methodology.

It appears likely that an even more collective and better means of treating variation in loading characteristics for contingency surfaces might readily be devised. One of two possible approaches to an ESWL basis for combining effects of widely varying types of loading probably will result in a superior methodology. It may be possible to combine effects of interacting wheels, for contingency surface purposes, by the same means as used for unsurfaced soils (see Figure 2). Some readily accomplished study will be needed to establish the suitability and degree of approximation of such means.

The second approach would be similar to the methodology used for the Aircraft Classification Number/Pavement Classification Number (ACN/PCN) method adopted by ICAO, the International Civil Aviation Organization, as the only acceptable means for aircraft weight bearing reporting (Reference 65). This method involves groupings of subgrade strengths so that the ESWL for an aircraft type can be considered, with sufficient accuracy, to be a constant proportion of wheel load within any subgrade strength group. This method would also require study which should be easily conducted.

Just as for use of the 13 groupings of aircraft, these ESWL methods would not satisfactorily treat tire pressure for unsurfaced or surface-critical areas. Some separate consideration of tire pressure will be needed.

B. LOAD REPETITIONS

It is well established that the supporting capacity of a pavement or unpaved operating area is some combination of load magnitude and repetitions of that load. The smaller the number of repetitions necessary, the larger can be the load supported for that number of repetitions.

Use of pavements or soil surfaces for contingency purposes is likely limited to no more than about 100 operations at the most and can be limited to only one or two passes. Thus, evaluation of contingency surfaces will be concerned, initially, with making one or two passes with only very low risk of not being able to complete the pass or passes. Beyond this, it will be desired to know how many multiple passes can be supported.

Deterioration with repetitions or passes is known to mature logarithmically so it will be necessary to evaluate for some pattern of repetitions such as complete with a high degree of certainty of 1, 10, and 100 passes and with low risk of misguidance evaluate for 3, 10, and 35 passes.

C. MATRIX OF SURFACING VERSUS OPERATIONAL NEED

As earlier discussed, contingency surfaces of concern might involve certain types of pavement or surface as bare soil (unlayered), layered soil with a stronger top layer or crust over a weaker underlayer or with a weak or soft surface layer over a firmer underlayer, gravel or other aggregate structural layer over a soil subgrade, but without surface paving of asphalt or concrete, flexible pavement of conventional structure including common bituminous surfacing over aggregate base or thick (full depth) bituminous top layer, rigid pavement of conventional structure including common jointed portland cement concrete (PCC), reinforced jointed PCC, continuously reinforced concrete pavement (CRCP), and PCC with either rigid or flexible overlay (Reference 5), weak top structure pavements including flexible pavements not designed for high tire pressure deteriorated and weakened base flexible pavements too thin surfacing over low fines noncohesive bases or too thin flexible or rigid structures over soft subgrades, and landing mat surfacing both light-duty and medium-duty types.

For satisfactory aircraft operation on contingency surfaces when used for taxiing, parking, or take-off and landing, response of the aircraft to the surfacing for each of the various operating modes must be evaluated. Response criteria are therefore needed for each pavement type for such operational concerns common rolling as for taxiing without significant turning or braking, turning while rolling, braking, parking or stopping with consequent settlement into depressions in weak surfaces, roughness, and drag.

The matrix presented earlier in Figure 3 relates these response criteria to surfacing type and provides a coding symbol for each, which attempts to characterize the criteria which have been developed that is applicable for dealing with them. Comments are presented for each matrix element.

1. Bare Soil

Common rolling on unlayered bare soil has been extensively studied, and existing criteria provide an adequate basis for development of a guide manual for BCE use in assessing operation on contingency surfaces. The SAFE study and other references cited earlier (References 6, 13, 15, 16, 28, and 49) as well as Figures 1 and 2 present applicable criteria. Deviations from common rolling are somewhat more demanding, and studies of turning, braking, and increased rutting depressions from stopping have been studied in the SAFE and other research efforts (References 25, 26, 27, 28, 71, 72, and 73). Resulting criteria are only nominally or partially adequate for separate dealing with the deviations from common rolling.

In the summary applications of SAFE study developments to the "User Guide" of Reference 49 effects of turning and light braking were included in the performance charts for taxiing operations. Also, the criteria of Figures 1 and 2 were found by the SAFE study to be somewhat conservative (for straight rolling behavior), and it is notable that Reference 49 performance chart criteria are about the same as equivalent criteria reflected by Figures 1 and 2 or in Reference 6 where the criteria are based on an earlier version of Figure 1 criteria. It is also notable that Reference 49 performance charts for parking areas show generally lower requirements than performance charts for taxiways except where very low soil strengths are involved.

While the demands of turning, braking, and stopping which are known to have requirements greater than simple rolling, the present state of technology development does not permit confident and readily usable applications to a manual for BCE use in the near future. Improvements to the technology must continue, but the next generation manual for BCE use in evaluating contingency surfaces should make use of a combined or conservative criteria basis which provides for rolling with some turning, braking, or stopping.

One shortcoming in the technology which should receive future study but which should also be the basis of operational warnings in the BCE manual is braking on unbound sands or sandy gravel soils. These materials which enjoy no cohesive binding are subject to much greater rutting under braked tires (References 71 and 80). The SAFE developments as reflected in the summary User Guide (Reference 49) are only for fine (cohesive) soils. The ground mobility studies, which provide a starting base for many of the unsurfaced soil developments for aircraft, have devised a clay mobility number and a sand mobility number recognizing different behavior in relation to slippage which is the equivalent of braking. The SAFE and most other studies have made developments based on the clay mobility number, since most soils contain a cohesive fines fraction. In the BCE manual there should be warning guidance that severe braking on unbound sand soils will result in severe rutting. For other operating modes the behavior differences are less profound, except for the braking type action of nose-wheel side trust on sharp turning.

Roughness of unsurfaced soil from both irregular surface and variation in soil strength are explained in Appendix E of Reference 47 and is treated in other parts of the SAFE study (References 32 and 33) using adaptations of the Air Force "have bounce" methods and criteria. Existing criteria are only "poor" but can be used. Probably for purposes of the BCE guide manual, it will only be possible to furnish some form of general guidance and warning of potential limitations.

Drag related to rutting of soft soils has been studied in the SAFE (Reference 28) and other programs (References 21, 74, 75, 76, and 77). Resulting criteria are nominally adequate for use in BCE guide manual development.

2. Layered Soils

The response of bare soil areas which are layered can be substantially influenced by the underlying layer. A softer lower layer will detract from the surface strength while a stiffer underlying soil will upgrade the surface strength. Means for evaluating layered soils of either combination were developed under the SAFE program (References 45 and 46), and the methods are treated in the user guide of Reference 49. These criteria are considered to be nominally adequate. They will be strengthened by further field verification.

Turning, braking, and stopping on layered soils are considered to relate to common rolling on layered soil in a manner similar to the comparison for unlayered soil. Thus, separate treatment for layered soils is not deemed to be needed. Separate treatment for roughness is similarly considered to be not separately needed.

Drag on layered soils is considered to be only poor but usable. For the soft surface over a firmer underlayer the determination of an equivalent strength unsurfaced soil may not be well related to drag, and there is little field verification to support the applicability.

3. Aggregate Top Layer

Gravel or aggregate surfaced pavements or operating areas have been shown to behave much like conventional flexible (asphalt surface) pavements, but they need only from 3/4 to 4/5 of the structure thickness since they can tolerate somewhat greater surface disruption (References 53 and 54). They are considered to have only nominally adequate validity because two different analyses of the data on which the criteria are based have led to two versions of the basis for evaluation. The method derived should also reflect evaluation results similar to those for a firmer soil over weaker underlying soil as discussed earlier for layered soils.

A brief study is needed to directly compare the layered soil doctrine (References 45, 46, and 49) with the two revisions of gravel service doctrine (References 53 and 54).

Turning, braking, parking, and drag on gravel surface layers (unless loose) are not considered to require separate criteria. The surface stability of gravel layers should prevent significant rutting so that these surfaces can be expected to behave much like lower quality flexible pavements.

Roughness is expected to be somewhat greater than for conventional surfaced pavements, but it is rated as having a nominally adequate basis for criteria formulation. The same PSD (Power Spectral Density) methods based on surface profiles that are used for conventional pavements in the Air Force "have bounce" methods are applicable.

4. Flexible Pavement

Design and evaluation methodology as reflected in Air Force manuals provides an adequate basis for contingency use evaluation of flexible (bituminous) pavements. The necessary extrapolations to the very low repetition levels of concern have had sufficient field verification for the basis to be considered adequate.

Because the structure must be adequate to protect its surface layer from severe distortion, there is no need for separate criteria to assess effects of turning, braking, stopping, or drag.

Roughness criteria as in use by Air Force in PSD "have bounce," and similar methods provide an adequate basis for roughness response evaluations. More recent studies in relation to rapid runway repair program are applicable. Reference 58 is an example of such study.

5. Rigid Overlay Pavement

Design and evaluation methodology as reflected in Air Force manuals for rigid (PCC) and for overlay pavements are as well founded as for flexible pavement, but they are rated less than completely adequate because of virtually no experience with failure at very low repetition levels, and because limits have not been established beyond which a heavy concentrated (high pressure) load will "punch through" a thin rigid surfacing over a weak supporting layer.

6. Weak Top Structure Pavements

Pavements whose near surface strength is only sufficient for lower tire pressures may appear to be of adequate thickness to protect the strength of subgrade it has in support of a contingency loading. If, however, the contingency loading is of higher tire pressure, the near surface and surface material strength will control evaluation of load support capacity. A parallel circumstance can exist for a structure originally designed to have good top strength but the structure has been abandoned or little used and allowed to deteriorate and lose strength through cracking and base saturation. Criteria for evaluating such pavements are considered to be poor but usable.

Turning and braking should not require separate criteria, but parking depressions could be a problem. Roughness and drag for these weak surface pavements may or may not be problems, but definitive criteria are unsatisfactory.

7. Landing Mat

Operating surfaces of airfield landing mat can be designed or evaluated using criteria as indicated in References 56, 57, 58, and 59 or in AFM 86-3, Volume II (Reference 6). These criteria are considered nominally adequate for development of BCE guidance in a contingency surface manual.

Turning and parking should require no separate criteria, but mat slippage on the subgrade as a result of heavy aircraft braking leads to special anchorage requirements or limited use warnings. Design basis is only partially adequate.

Limited tests over 30 years ago (Reference 78) provide some information on rolling resistance or drag. The report of these tests also indicates that the mat surface unloaded and the loaded surface are not the same. Therefore, roughness cannot be directly related to unloaded profile. Both roughness and drag are considered to have only a poor basis for criteria formulation.

SECTION VI

LANDING SURFACE ATTRIBUTE ASSESSMENT

A. ATTRIBUTES

To permit evaluation of a pavement, it is necessary to assess certain attributes or characteristics of the pavement either directly or indirectly by nondestructive evaluation means. Accordingly, a manual for BCE to use in evaluating operating surfaces will need to provide guidance toward determining the required attribute parameters. The existing methods and technology applicable to assessing the evaluation input parameters were discussed at length in Section V. Because attributes vary by surfacing type, means for their determination also vary by surfacing type.

B. MATRIX OF SURFACING TYPE VERSUS ATTRIBUTE ASSESSMENTS

Figure 4 presents a matrix of operating surface type versus the attributes which must be assessed to permit evaluation of the surface for determination of aircraft support capability. Coding in the matrix indicates need for discussion of assessment means in the manual for BCE guidance.

Surface	Subgrade Strength	Subgrade Strength	Structure Thickness	Direct Evaluation	Wheel-path Profiles
Bare soil	D	N	N	D	D
Layered Soil	D	D	D	D	D
Aggregate top Layer	D	D	D	D	D
Flexible Pavement	D	D	D	D	D
Rigid and Overlay Pavement	N	D	D	D	D
Weak Top Structure Flexible Pavement	D	N	D	D	D
Landing Mat	N	D	N	N	D

D - Discuss applicable methods.

N - Not required or no feasable means.

Figure 4. Landing Surface Attribute Assessment.

SECTION VII

CONCLUSIONS

A. RESULTS

1. Survey and Assessment

The technology has been surveyed and assembled in relation to development of a manual for use by BCE in evaluating operating surfaces for contingency use. Guidance to established methodology and source material have been described for use in final development of the planned manual. Gaps or shortcomings in the technology have been determined in relation to both short-term and long-term needs. Short-term needs can likely be satisfied for use in the BCE manual intended to be compiled in the near future. Long-term needs will require more time to develop useful results.

2. Short-Term Needs

This study has indicated examinations or developments which should, and likely can, be completed for use in a BCE guide manual for evaluation of contingency surfaces.

A careful comparative analysis should be made of the performance charts presented in the SAFE study summarizing User Guide (Reference 49) with a view to select a single set of data curves for each aircraft in lieu of the two for taxiways and parking areas (3 for F-4). This is justified by the limited accuracy of many other aspects of the evaluation technology and will lessen confusion for the BCE.

The criteria should also be compared with results of the nomograph included in Figure 1. If satisfactory criteria can be presented as in Figures 1 and 2, the need for individual aircraft criteria or even grouped aircraft criteria can be eliminated for unsurfaced soil operating areas. This will not only simplify the evaluation process for the BCE, but it will improve accuracy over the aircraft grouping option.

The basis of criteria for layered soil where a stronger layer overlies a weaker soil and of criteria for gravel or aggregate layers over a weaker subgrade, which is available in two versions, are all attempts to provide essentially the same basis for evaluating the stronger unsurfaced layer over a weaker subgrade. These should be carefully compared, and a single basis for treating this type operating surface should be devised.

An ESWL method for the relatively thin (in the range of half the thickness for a full normal design) conventional type flexible pavements should be devised if feasible. It is envisioned that a method similar to that involved in Figure 2 for unsurfaced soils may be possible, but other options should also be considered. This type of development would reduce the need to consider individual aircraft or grouping of aircraft for evaluation of flexible pavements.

Something similar to the ESWL for flexible pavements should be attempted for (thin) rigid and overlay pavements. No potentially fruitful approach can be suggested. If the ESWL method envisioned prove unsuccessful a method similar to that used for the ICAO ACN/PCN method for aircraft weight bearing reporting (Reference 65) can be devised. This involves developing approximately unique equivalent aircraft weights for the various aircraft types of concern for each of several ranges of subgrade strength and using these to relate evaluations for a standard type loading to any aircraft type. This will permit a BCE to evaluate for only the standard type loading and use the equivalent aircraft weight established in advance to arrive at any desired aircraft weight evaluation. This would reduce the need to deal directly with individual or groups of aircraft separately for conventional type pavements.

It would be well to consider whether the ESWL method inherent in Figure 2 or the derivation mentioned above will better treat evaluations for multiple-wheel aircraft for strong layer-over-subgrade (unsurfaced) operating areas.

Of only low priority, but necessary to complete the pattern of needed evaluation capability for BCE manual, is an ESWL for "light-duty mat" consistent with that of Reference 57.

3. Long-Term Needs

Technology needs or shortcomings are identified but they will require time and effort beyond what might reasonably be completed in time to be useful toward the contemplated BCE manual for evaluation of contingency surfaces.

The SAFE study provided a model for prediction of stop and start-up performance, but did not extend to providing the soil data needed to satisfactorily establish model parameters (Reference 49). This remains a requirement.

The SAFE study devised means for assessing braked-motion response of soil operating areas, but did not extend to multiple-pass verification (Reference 49). This also remains a requirement.

The SAFE study also covered performance of F-4 type aircraft in turn around areas (Reference 49), and the methodology should apply more generally to single-wheel aircraft. However, the methods do not extend to multiple-wheel aircraft. For treatment of multiple-wheel aircraft in turn around areas remains a need.

Some limited treatments of operations on unbound (no-fines sands and gravelly-sands) soils were included in the SAFE and other studies, but the SAFE study summarizing User Guide (Reference 49) is limited to fine (cohesive) soils. It has been demonstrated (References 71 and 80) that rutting of unbound soils on braking is much more severe than for fine, cohesive soils. An extensive study of this problem is needed to expand the technology to cover this shortcoming.

High speed response to roughness on conventional pavements have been studied (Reference 74 as example), and effects of speed on wheel drag and rutting have been studied (References 77 through 80) for soil surface operations. The SAFE study examined deformable soil roughness at taxi speeds, but the summarizing User Guide (Reference 49) did not extend to roughness and drag for take-off and landing on soil surfaces. These analyses and methods developments are needed.

Rapid assessment of soil strength, whether in unsurfaced operating areas or subgrades beneath pavements, is required for contingency surface evaluation. The automated trafficability cone penetrometer has been used successfully in the SAFE program and can be used for rapid measurement of soil strength. There is, however, strong interest in other cone devices (References 65 and 66) for soil strength measurement. Each such device has favorable and not so desirable characteristics. It would be desirable to develop a readily field cone device which correlates well with CBR and other cone instrument measurements, which can measure over a broad range in strength that can penetrate strong crust type layers that will not quickly exhaust users.

Recent (not yet published) work by Dr. Bush of WES related to the NDT comparative study supported by the Air Force indicates excellent capability for prediction of low pass level evaluation of flexible pavement behavior. Also, the early trials of falling weight deflectometer (FWD) assessment of unsurfaced soil strength have shown promise. A program is needed to study the applicability of NDT methods to evaluate unsurfaced operating areas and pavements for contingency use.

Only little if any verification exists for the limiting load behavior of rigid pavements at very low repetition levels. Thus, this phase of technology needs further examination. There is also little established guidance as to how thin a rigid pavement or rigid pavement with some overlay might be subject to sudden break-through when only weakly supported and intensely loaded. This is a further aspect of technology needing study. NDT methods are being used to evaluate conventional pavements and have been applied to gravel surfaced and unsurfaced areas with some success. For such NDT methods to become universally applicable, they need to be developed for application to airfield landing mat surfaces.

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