E.2 FAA厚度設計法之簡介

23.5.2 鋪面厚度設計

1.柔性鋪面之厚度設計

FAA 發展出一套機場柔性鋪面之設計方法，此方法建議對路基土壤之物理特性作徹底的調查，並依統一土壤分類法(Unified Soil Classification System)判定路基土壤之類別。

統一土壤分類法係由美國的陸軍工兵團 (Army Corps of Engineers)所發展，此分類法根據土壤顆粒之粗細、級配、塑性及壓縮性等，將土壤分成粗粒土壤、細粒土壤、高度有機質土壤三大類。另再分爲十五細目，每一細目以兩個字母作代號；第一個字母表示影響土壤性能最大的主要成分，計分六種：礫 (G)、砂 (S)、沉泥 (M) 、黏土 (C)、有機質沉泥或黏土 (O)、泥炭 (Pt)；第二個字母表示其顆粒級配性質、塑性以及次要成分，計分四種：優良級配 (W)、不良級配 (P)、低塑性 (L)、高塑性 (H)。

粗粒土壤係指未通過#200篩的分量在50%以上者。凡粗粒土壤留於#4篩的分量在50%以上者稱爲礫石 (Gravel) ，一共分成四個細目計：GW、GP、GM、GC；留於#4篩少於50%者稱爲砂 (Sand) ，亦分成四個細目計：SW、SP、SM、SC。

細粒土壤係指通過#200篩的分量在50%以上者。凡細粒土壤的液性限度 (Liquid Limit) 小於50者，一共分成三個細目計：ML、CL及OL；液性限度大於50者，亦分成三個細目計：MH、CH及OH。

高度有機質土壤包括泥炭、砂質泥炭與黏質泥炭，以Pt 表示。

統一土壤分類法可列如表23-4。

在此須說明的是，統一土壤分類法僅能概略地表示路基土壤的特性，因此FAA 建議應作CBR 試驗。此試驗係由美國加州公路局研究成功之一種測定路基土壤抗剪力試驗方法，CBR 之涵義則爲夯實土壤的貫入抗力與標準土壤貫入抗力的比值，以百分率表示。所謂標準土壤之貫入抗力，則爲用一定級配之碎石，納入規定之模筒，受規定之夯實能量，再浸入水內若干規定時間，再根據標準試驗方法，測定貫入深度在0.25cm時之所施壓力而言。由CBR 值即可準確表明路基土壤之強度，各類土壤之相對CBR 值列於表23-4中。

FAA 的設計方法主要係依據路基土壤的CBR 值、飛機之全重 (Gross Aircraft Weight)及每年離地的飛機數量三項因素設計鋪面之厚度，並依降落裝置 (Landing Gear) 分爲單輪、雙輪及雙輪縱排 (Dual-tandem)等繪製設計曲線圖。此外，並對B-747、DC-10及L-1011等廣體客機個別製作設計曲線圖。

圖23-3爲雙輪降落裝置之柔性鋪面設計曲線圖。由於落地飛機之全重平均約爲離地飛機之75%，因此圖中之飛機全重係以最大的離地飛機全重爲準；在每年離地的飛機數量一項，則須考慮各型飛機輪重之累加效應 (Cumulative Effect)，而爲了設計方便，可將各型飛機之輪重換算爲設計機型，其當量 (Equivalence)之換算式如下：

表 23-4 統一土壤分類及相對應之CBR 值與k 值表

主要分類		簡號	土壤說明	CBR 值	路基係數k(kg / cm^3)
粗粒土壤，留存在#200篩的份量佔全重50%以上	礫石土（留存在#4號篩的佔全重的50%以上）	GW	級配優良的礫石與砂質礫。	60～80	≧ 8.3
		GP	跳越級配或均勻的礫石、砂質礫	35～60	≧ 8
		GM	沉泥質礫、黏土質砂礫。	40～80	≧ 8
		GC	黏土質礫、黏土質砂礫。	20～40	6～8
	砂質土（通過#4號篩的佔全重的50%以上）	SW	級配優良的砂、礫質砂。	20～40	6～8
		SP	跳越級配或均勻砂、礫質砂。	15～25	6～8
		SM	沉泥質砂、沉泥質礫砂。	20～40	6～8
		SC	黏土質沉泥、黏土質礫砂。	10～20	6～8
細粒土壤，通過#200篩的佔全重50%以上	可壓縮性低，液性限度小於50。	ML	沉泥、極細砂、沉泥質或黏土質砂、雲母質沉泥。	5～15	3～6
		CL	低塑性黏土、砂質或沉泥質黏土	5～15	3～6
		OL	有機質沉泥與黏土具低塑性者。	4～8	3～6
	可壓縮性高，液性限度大於50。	MH	雲母質沉泥、矽藻土、火山灰。	4～8	3～6
		CH	高塑性黏土、與砂質黏土。	3～5	1.5～3
		OH	有機質沉泥與黏土具高塑性者。	3～5	1.5～3
土內含有纖維狀有機質		Pt	泥炭、砂質泥炭與黏質泥炭。	—	—

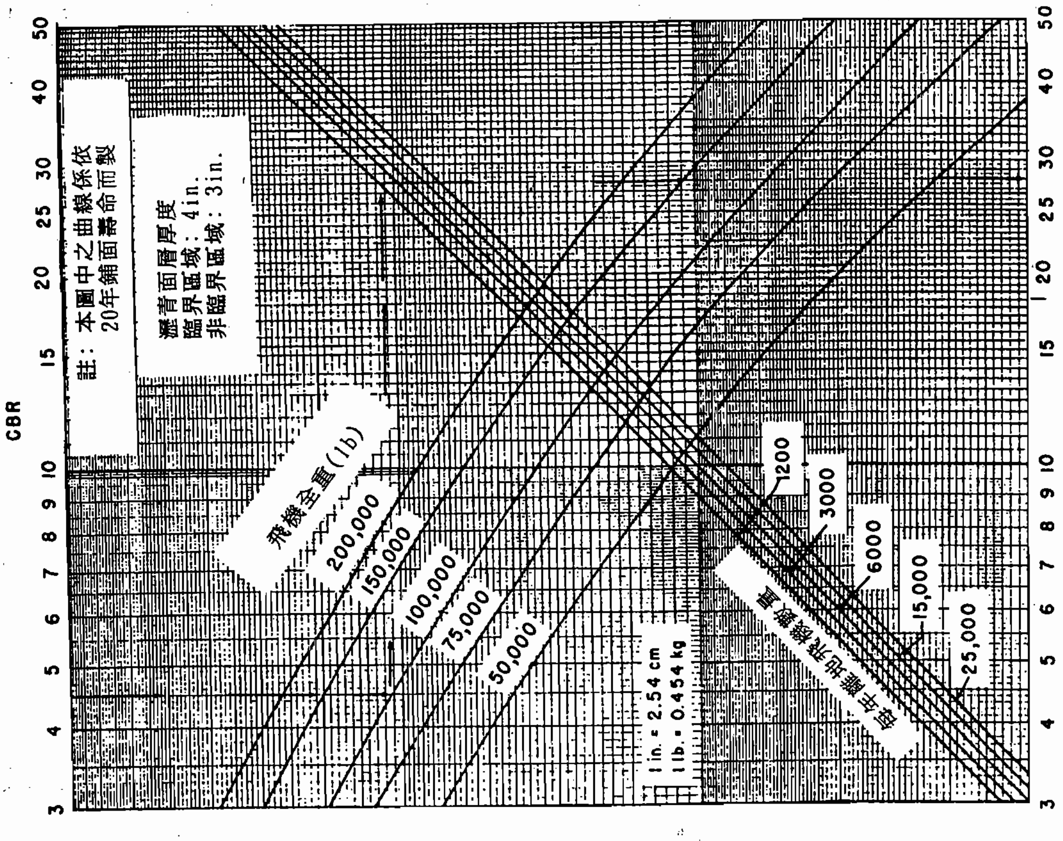


圖 23-3 柔性鋪面臨界區域之厚度設計曲線圖，雙輪降落裝置（資料來源：[9]）

$$\log R_i = \log[R_d](\frac{W_d}{W_i})^{1/2}$$

$$\cancel{E_i = \frac{R_i}{R_d}}$$

式中，

R$_d$ 爲設計機型離地之~~全重~~ 等效起飛次數當量 (Equivalent Annual Departures)

R$_i$ 爲i 型飛機離地之~~全重~~ 年起飛次數

W$_d$ 爲設計機型離地之輪重

W$_i$ 爲i 型飛機離地之輪重

~~E$_i$ 爲i 型飛機換算爲設計機型之當量~~

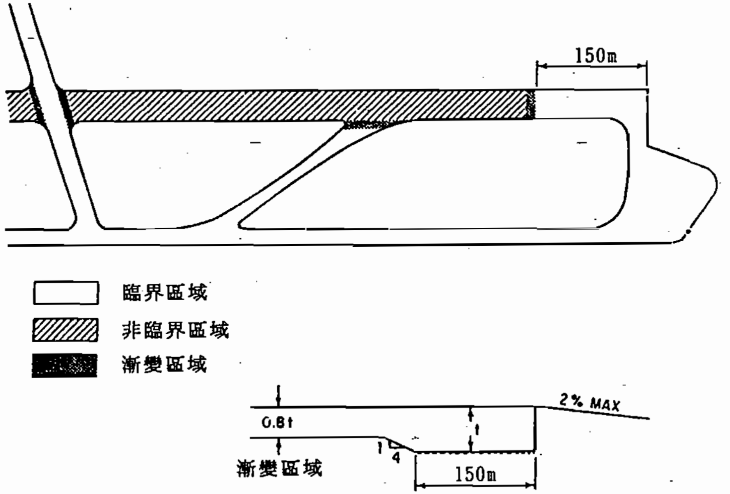
圖23-3係用以設計機場臨界區域之鋪面厚度。所謂臨界區域（Critical Area)，係指跑道- 滑行道系統中承受最大密集壓力之區域，包括跑道端部、所有滑行道及停機坪，如圖23-4所示。此區域之鋪面厚度須較大，其他非臨界區域之鋪面厚度可減少20%。

圖23-3之使用方法爲：依據路基土壤之CBR 値在圖中上面之座標找到一點，再往下作垂直線與對應之飛機全重曲線相交，再由此交點作水平線與對應之全年離地飛機數量線相交，由此交點作垂直線即可在下面之座標求得臨界區域之鋪面厚度。

圖23-5爲全重在13,600kg (30,000 lb)以下輕型飛機之鋪面厚度設計圖，由此圖所得出之厚度同時適用於臨界區域與非臨界區域，而不須作任何折減。

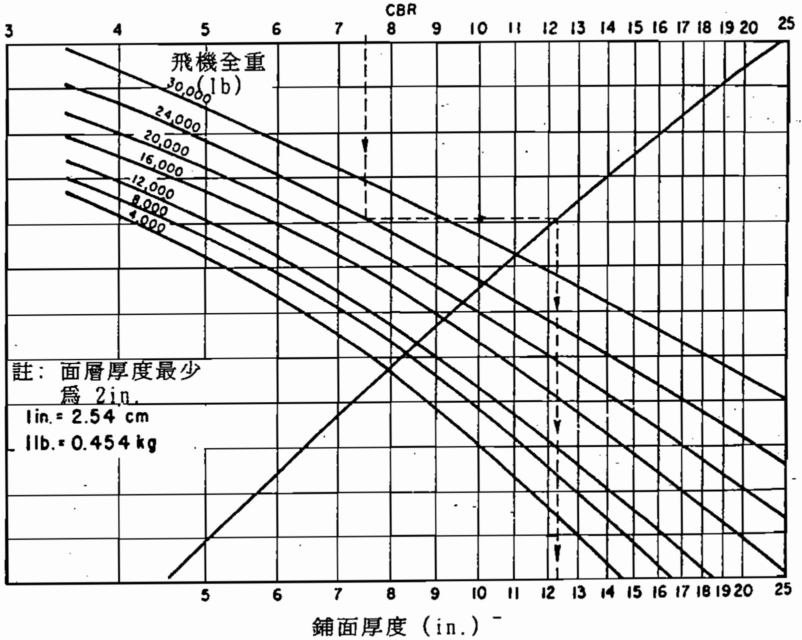
2.剛性鋪面之厚度設計

FAA 針對剛性鋪面所發展之厚度設計方法與柔性鋪面之設計方法相類似。其設計曲線圖所包含之設計要素爲混凝土之撓曲強度（



註：t爲柔性鋪面的全厚度或剛性鋪面的混凝土面版厚度

圖 23-4 機場鋪面之臨界區域圖 (資料來源：[10])



註：面層厚度最少爲 2in.
1in.= 2.54 cm
1lb.= 0.454 kg

圖 23-5 輕型飛機之柔性鋪面厚度設計曲線圖
(資料來源：[9])

Flexural Stength）、路基係數（Subgrade Modulus）、飛機全重及每年離地飛機數量。

路基係數係產生單位沉陷所需之壓力，亦稱爲路基抗力係數（Coefficient of Subgrade Reaction），以k 表示，其定義爲單位壓力（kg／cm²)除以單位沉陷量（cm），因此其單位爲kg／cm³ 。k 值之測定乃以 75 cm直徑之圓鈑載重試驗依AASHTO所訂之T-222試驗程序測得。若圓鈑載重試驗不易實施，則可採用表23-4中之k值。

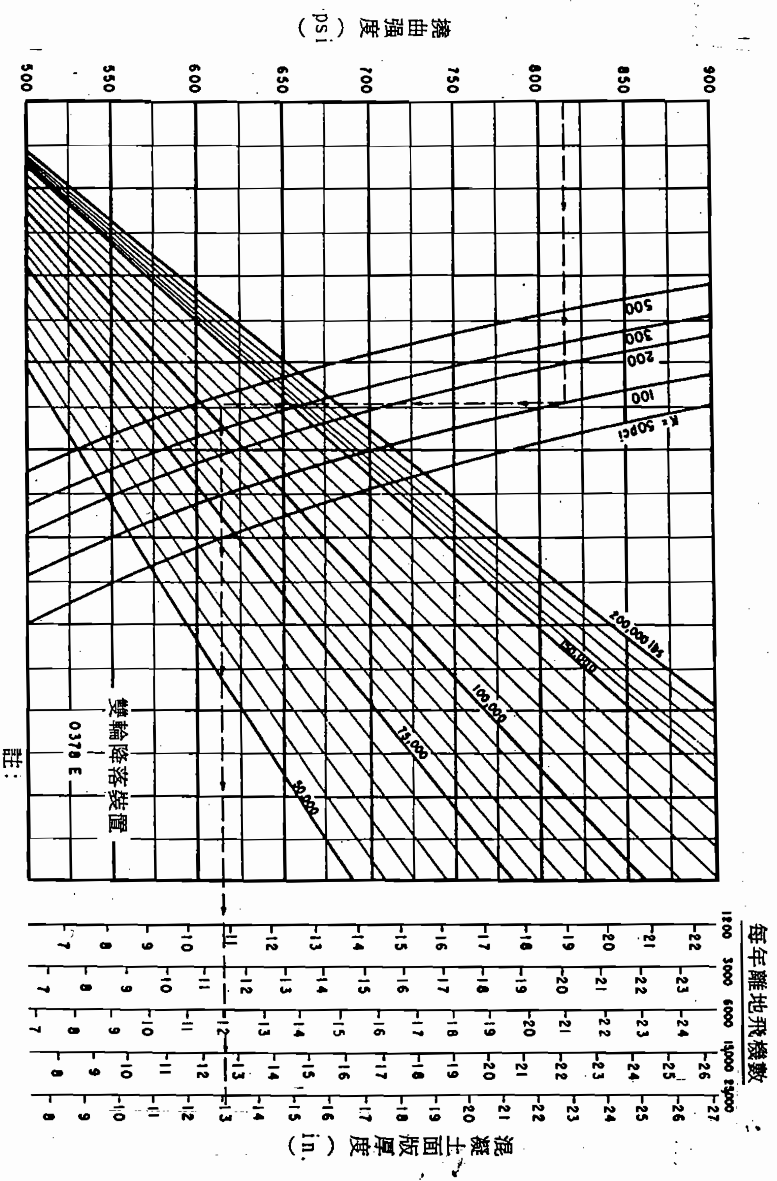
圖23-6爲雙輪降落裝置之剛性鋪面設計曲線圖，此圖之使用方法與圖23-3相同。由圖中所得之厚度爲臨界區域之厚度，在非臨界區域則可減少20％之厚度，但總厚度不可少於15cm。

FAA 又規定，除了表23-5中所列之地區外，剛性鋪面至少應有10cm之基層。若基層之厚度再增加，則有提高路基係數及減少混凝土面版厚度之效益，其取捨主要依經濟的觀點而定。

機場剛性鋪面之接縫及鋼筋設計與公路鋪面相似，但因機場鋪面之厚度較大，其所需路面版之寬度較寬，合釘亦較大。縱向接縫（Longitudinal Joint）之間距在面版厚度爲25cm以下時爲 3.8 m，面版厚度在25cm以上時，間距可爲3.8～7.6 m。

表 23-5　機場鋪面構造不需基層之地區表

土壤分類	排水良好		排水不良	
	無冰凍	冰凍	無冰凍	冰凍
GW	v	v	v	v
GP	v	v	v	
GM	v			
GC	v			
SW	v			



註：
1 inch=2.54 cm　1 psi=0.0069 MN/m²
1 lb =0.454 kg　1 pci=0.272 MN/m³

圖 23-6　剛性鋪面臨界區域之厚度設計曲線圖，雙輪降落裝置（資料來源：[9]）

CHAPTER 3. PAVEMENT DESIGN.

SECTION 1. DESIGN CONSIDERATIONS

15. SCOPE. This chapter covers pavement design for airports serving aircraft with gross weights of 30,000 pounds (13 000 kg) or more. Chapter 5 is devoted to the design of pavements serving lighter aircraft with gross weights under 30,000 pounds (13 000 kg).

16. DESIGN PHILOSOPHY. The FAA policy of treating the design of aircraft landing gear and the design and evaluation of airport pavements as three separate entities is described in the Foreword to this advisory circular. The design of airport pavements is a complex engineering problem which involves a large number of interacting variables. The design curves presented in this chapter are based on the CBR method of design for flexible pavements and a jointed edge stress analysis for rigid pavements. These procedures represent a change from prior FAA design methods and will result in slightly different pavement thicknesses. The design curves in this chapter will satisfy the standards required by Section 16(a) of the Airport and Airway Development Act of 1970, as amended. Other design procedures such as those based on layered elastic analysis and those developed by The Asphalt Institute and the Portland Cement Association may be utilized to determine pavement thicknesses when approved by the FAA. These procedures will yield slightly different design thicknesses due to different basic assumptions. All pavement designs should be summarized on FAA Form 5100-1, Airport Pavement Design, (see AC 150/5100-3A) which is considered to be part of the Engineer's Report. Because of thickness variations, the evaluation of existing pavements should be performed using the same method as was employed in the design. Procedures to be used in evaluating pavements are described in detail in Chapter 6 of this advisory circular. Details on how the new FAA methods of design were developed are as follows:

a. Flexible Pavements. The flexible pavement design curves presented in this chapter are based on the California Bearing Ratio (CBR) method of design. The CBR design method is basically empirical; however, a great deal of research has been done with the method and reliable correlations have been developed. Gear configurations are related using theoretical concepts as well as empirically developed data. The design curves provide the required total thickness of flexible pavement (surface, base, and subbase) needed to support a given weight of aircraft over a particular subgrade. The curves also show the required surface thickness. Minimum base course thicknesses are shown on a separate curve. A more detailed discussion of CBR design is presented in Appendix 2.

b. Rigid Pavements. The rigid pavement design curves in this chapter are based on the Westergaard analysis of edge loading. The edge loading analysis has been modified to simulate a jointed edge condition. Design curves are furnished for areas where traffic will predominantly follow parallel to the joints and for areas where traffic is likely to cross joints at some acute angle. Previous FAA rigid pavement criteria were based on an interior loading assumption. Pavement stresses are higher at the jointed edge than at the slab interior. Test validations and field performance show practically all load induced cracks develop at the jointed edge and migrate toward the slab interior. For these reasons the basis of design was changed from interior to jointed edge, as recommended by the U. S. Army Corps of Engineers, under a pavement research contract for the FAA. The design curves contain lines for five different annual traffic volumes. The thickness of pavement determined from the curves is for slab thickness only. Subbase thicknesses are determined separately. A more detailed discussion of the basis for rigid pavement design is presented in Appendix 2.

17. BACKGROUND. An airfield pavement and the operating aircraft represent an interactive system which must be recognized in the pavement design process. Design considerations associated with both the aircraft and the pavement must be satisfied in order to produce a satisfactory design. Careful construction control and some degree of maintenance will be required to produce a pavement which will achieve the intended design life. Pavements are designed to provide a finite life and fatigue failures are anticipated. Poor construction and lack of preventative maintenance will usually result in disappointing performance of even the best designed pavement.

a. The determination of pavement thickness requirements is a complex engineering problem. Pavements are subject to a wide variety of loadings and climatic effects. The design process involves a large number of interacting variables which are often difficult to quantify. Although a great deal of research work has been completed and more is underway, it has been impossible to arrive at a direct mathematical solution of thickness requirements. For this reason the determination of pavement thickness must be based on the theoretical analysis of load distribution through pavements and soils, the analysis of experimental pavement data, and a study of the performance of pavements under actual service conditions. Pavement thickness curves presented in this chapter have been developed through correlation of the data obtained from these sources. Pavements designed in accordance with these standards are intended to provide a structural life of 20 years that is free of major maintenance if no major changes in forecast traffic are encountered. It is likely that rehabilitation of surface grades and renewal of skid resistant properties will be needed before 20 years due to destructive climatic effects and deteriorating effects of normal usage.

b. The structural design of airport pavements consists of determining both the overall pavement thickness and the thickness of the component parts of the pavement. There are a number of factors which influence the thickness of pavement required to provide satisfactory service. These include the magnitude and character of the aircraft loads to be supported, the volume of traffic, the concentration of traffic in certain areas, and the quality of the subgrade soil and materials comprising the pavement structure.

18. AIRCRAFT CONSIDERATIONS.

a. Load. The pavement design method is based on the gross weight of the aircraft. For design purposes the pavement should be designed for the maximum takeoff weight of the aircraft. The design procedure assumes 95 percent of the gross weight is carried by the main landing gears and 5 percent is carried by the nose gear. AC 150/5325-5, Aircraft Data, lists the weight of nearly all civil aircraft. The maximum takeoff weight should be used in calculating the pavement thickness required. Use of the maximum takeoff weight is recommended to provide some degree of conservatism in the design and is justified by the fact that changes in operational use can often occur and recognition of the fact that forecast traffic is approximate at best. By ignoring arriving traffic some of the conservatism is offset.

b. Landing Gear Type and Geometry.

(1) The gear type and configuration dictate how the aircraft weight is distributed to the pavement and determine pavement response to aircraft loadings. It would have been impractical to develop design curves for each type of aircraft. However, since the thickness of both rigid and flexible pavements is dependent upon the gear dimensions and the type of gear, separate design curves would be necessary unless some valid assumptions could be made to reduce the number of variables. Examination of gear configuration, tire contact areas, and tire pressure in common use indicated that these follow a definite trend related to aircraft gross weight. Reasonable assumptions could therefore be made and design curves constructed from the assumed data. These assumed data are as follows:

(a) Single Gear Aircraft. No special assumptions needed.

(b) Dual Gear Aircraft. A study of the spacing between dual wheels for these aircraft indicated that a dimension of 20 inches (0.51 m) between the centerline of the tires appeared reasonable for the lighter aircraft and a dimension of 34 inches (0.86 m) between the centerline of the tires appeared reasonable for the heavier aircraft.

(c) Dual Tandem Gear Aircraft. The study indicated a dual wheel spacing of 20 inches (0.51 m) and a tandem spacing of 45 inches (1.14 m) for lighter aircraft, and a dual wheel spacing of 30 inches (0.76 m) and a tandem spacing of 55 inches (1.40 m) for the heavier aircraft are appropriate design values.

(d) Wide Body Aircraft. Wide body aircraft; i.e., B-747, DC-10, and L-1011 represent a radical departure from the geometry assumed for dual tandem aircraft described in paragraph (c) above. Due to the large differences in gross weights and gear geometries, separate design curves have been prepared for the wide body aircraft.

(2) Tire pressure varies between 75 and 200 psi (516 to 1 380 kPa) depending on gear configuration and gross weight. It should be noted that tire pressure asserts less influence on pavement stresses as gross weight increases, and the assumed maximum of 200 psi (1 380 kPa) may be safely exceeded if other parameters are not exceeded.

c. Traffic Volume. Forecasts of annual departures by aircraft type are needed for pavement design. Information on aircraft operations is available from Airport Master Plans, Terminal Area Forecasts, the National Airport System Plan, Airport Activity Statistics and FAA Air Traffic Activity. These publications should be consulted in the development of forecasts of annual departures by aircraft type.

19. DETERMINATION OF DESIGN AIRCRAFT. The forecast of annual departures by aircraft type will result in a list of a number of different aircraft. The design aircraft should be selected on the basis of the one requiring the greatest pavement thickness. Each aircraft type in the forecast should be checked to determine the pavement thickness required by using the appropriate design curve with the forecast number of annual departures for that aircraft. The aircraft type which produces the greatest pavement thickness is the design aircraft. The design aircraft is not necessarily the heaviest aircraft in the forecast.

20. DETERMINATION OF EQUIVALENT ANNUAL DEPARTURES BY THE DESIGN AIRCRAFT.

a. Since the traffic forecast is a mixture of a variety of aircraft having different landing gear types and different weights, the effects of all traffic must be accounted for in terms of the design aircraft. First, all aircraft must be converted to the same landing gear type as the design aircraft. The following conversion factors should be used to convert from one landing gear type to another:

To Convert From	To	Multiply Departures By
single wheel	dual wheel	0.8
single wheel	dual tandem	0.5
dual wheel	dual tandem	0.6
double dual tandem	dual tandem	1.0
dual tandem	single wheel	2.0
dual tandem	dual wheel	1.7
dual wheel	single wheel	1.3
double dual tandem	dual wheel	1.7

Secondly, after the aircraft have been grouped into the same landing gear configuration, the conversion to equivalent annual departures of the design aircraft should be determined by the following formula:

$$\log R_1 = \log R_2 \times \left(\frac{W2}{W_1}\right)^{\frac{1}{2}}$$

where R_1 = equivalent annual departures by the design aircraft

R_2 = annual departures expressed in design aircraft landing gear

W_1 = wheel load of the design aircraft

W_2 = wheel load of the aircraft in question

For this computation 95 percent of the gross weight of the aircraft is assumed to be carried by the main landing gears. Wide body aircraft require special attention in this calculation. The procedure discussed above is a relative rating which compares different aircraft to a common design aircraft. Since wide body aircraft have radically different landing gear assemblies than other aircraft, special considerations are needed to maintain the relative effects. This is done by treating each wide body as a 300,000-pound (136 100 kg) dual tandem aircraft when computing equivalent annual departures. This should be done in every instance even when the design aircraft is a wide body. After the equivalent annual departures are determined, the design should proceed using the appropriate design curve for the design aircraft. For example if a wide body is the design aircraft, all equivalent departures should be calculated as described above; then the design curve for the wide body should be used with the calculated equivalent annual departures.

b. Example: Assume an airport pavement is to be designed for the following forecast traffic:

Aircraft	Gear Type	Forecast Annual Departures	Maximum Takeoff Weight lbs.	(kg)
727-100	dual	3,760	160,000	(72 600)
727-200	dual	9,080	190,500	(86 500)
707-320B	dual tandem	3,050	327,000	(148 500)
DC-9-30	dual	5,800	108,000	(49 000)
CV-880	dual tandem	400	184,500	(83 948)
737-200	dual	2,650	115,500	(52 440)
L-1011-100	dual tandem	1,710	450,000	(204 120)
747-100	double dual tandem	85	700,000	(317 800)

(1) Determine Design Aircraft. A pavement thickness is determined for each aircraft in the forecast using the appropriate design curves. The pavement input data, CBR, K value, flexural strength, etc., should be the same for all aircraft. Aircraft weights and departure levels must correspond to the particular aircraft in the forecast. In this example the 727-200 requires the greatest pavement thickness and is thus the design aircraft.

(2) Group Forecast Traffic into Landing Gear of Design Aircraft. In this example the design aircraft is equipped with a dual wheel landing gear so all traffic must be grouped into the dual wheel configuration.

(3) Convert Aircraft to Equivalent Annual Departures of the Design Aircraft. After the aircraft mixture has been grouped into a common landing gear configuration, the equivalent annual departures of the design aircraft can be calculated.

$160{,}000 \times 0.95 \times \frac{1}{2} \times \frac{1}{2}$

Aircraft	Dual Gear Departures	Wheel Load lbs.	Wheel Load (kg)	Wheel Load of Design Aircraft lbs.	Wheel Load of Design Aircraft (kg)	Equivalent Annual Departures Design Aircraft
727-100	3,760	38,000	(17 240)	45,240	(20 520)	1,891
727-200	9,080	45,240	(20 520)	45,240	(20 520)	9,080
707-320B	5,185	38,830	(17 610)	45,240	(20 520)	2,764
DC-9-30	5,800	25,650	(11 630)	45,240	(20 520)	682
CV-880	680	21,910	(9 940)	45,240	(20 520)	94
737-200	2,650	27,430	(12 440)	45,240	(20 520)	463
747-100	145	35,625 1/	(16 160)	45,240	(20 520)	83
L-1011-100	2,907	35,625 1/	(16 160)	45,240	(20 520)	1,184
					Total	16,241

3050×1.7

400×1.7

$300{,}000 \times 0.95 \times \frac{1}{4} \times \frac{1}{2}$

1/ Wheel loads for wide body aircraft will be taken as the wheel load for a 300,000-pound (136 100 kg) aircraft for equivalent annual departure calculations.

(4) For this example the pavement would be designed for 16,000 annual departures of a dual wheel aircraft weighing 190,500 pounds (86 500 kg). The design should, however, provide for the heaviest aircraft in the traffic mixture when considering depth of compaction, thickness of asphalt surface, drainage structures, etc.

21. TRAFFIC DISTRIBUTION.

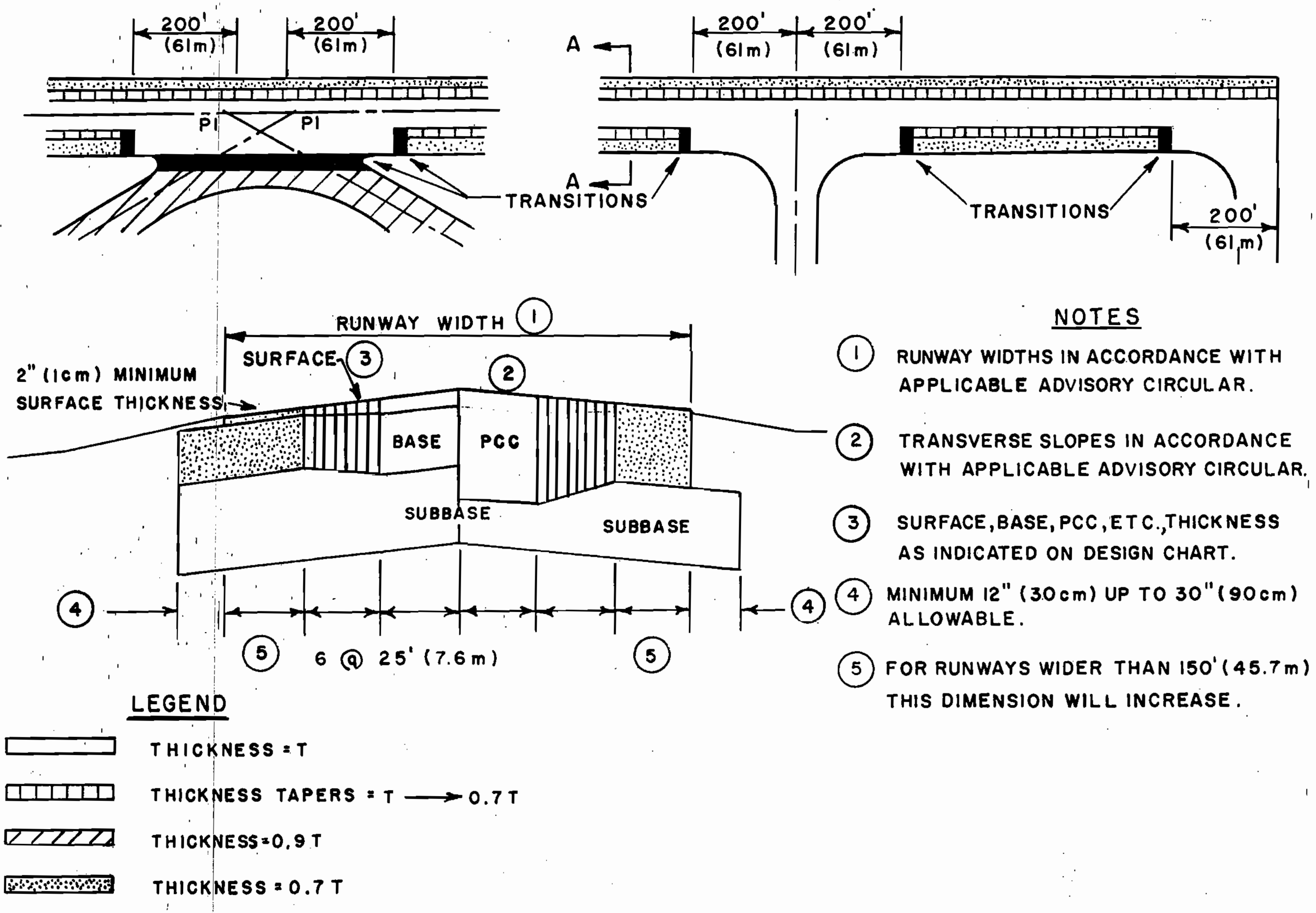
a. Research studies have shown that aircraft traffic is distributed laterally across runways and taxiways according to statistically normal (bell shaped) distribution. FAA Report No. FAA-RD-36, Field Survey and Analysis of Aircraft Distribution on Airport Pavements, dated February 1975, contains the latest research information on traffic distribution. The design procedures presented in this circular incorporate the statistically normal distribution in the departure levels.

b. In addition to the lateral distribution of traffic across pavements, traffic distribution and nature of loadings are considered at runway ends, aprons, and high speed turnoffs.

22. TYPICAL SECTIONS. Typical plan and cross section drawings for runway pavements are shown in Figure 3-1. These typical sections are intended for runways to serve jet powered aircraft. Deviations from these typical sections will be common due to the change inherent in staged construction projects where runways are extended and the location of taxiways is uncertain. As a general rule-of-thumb the designer should specify full pavement thickness T where departing traffic will be using the pavement; pavement thickness of 0.9T will be specified where traffic will be arrivals such as high speed turnoffs; and pavement thickness of 0.7T will be specified where pavement is required but traffic is unlikely such as along the extreme outer edges of the runway. Note that the full-strength keel section has been reduced to 50 feet (15 m) on the basis of the research study discussed in paragraph 21.

23. CLIMATIC CONSIDERATIONS.

a. General. The design of an airport pavement must consider the climatic conditions which will act on the pavement during its construction and life. Most climatic effects such as protection of the pavement during curing, laydown temperatures, etc., are handled by construction specifications and local construction experience.



NOTES

① RUNWAY WIDTHS IN ACCORDANCE WITH APPLICABLE ADVISORY CIRCULAR.

② TRANSVERSE SLOPES IN ACCORDANCE WITH APPLICABLE ADVISORY CIRCULAR.

③ SURFACE, BASE, PCC, ETC., THICKNESS AS INDICATED ON DESIGN CHART.

④ MINIMUM 12" (30cm) UP TO 30" (90cm) ALLOWABLE.

⑤ FOR RUNWAYS WIDER THAN 150' (45.7m) THIS DIMENSION WILL INCREASE.

LEGEND

☐	THICKNESS = T
▥	THICKNESS TAPERS = T ⟶ 0.7T
▨	THICKNESS = 0.9T
░	THICKNESS = 0.7T

FIGURE 3-1. TYPICAL PLAN AND CROSS SECTION FOR RUNWAY PAVEMENTS