Rigid Pavement Design for Ports in Chile

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A case study of rigid pavement design for two ports located in the central zone of Chile, which is an area of high seismic risk, is presented. Special considerations were required to address the problem of liquefiable subgrade soils that were the cause of severe damage to existing pavements during the large earthquake of March 3, 1985. Rational design charts were developed for rigid pavements on the basis of tensile stresses induced by critical edge loads. Slab stresses were evaluated by using two computer codes, and tensile stress-slab thickness relationships were developed for various values of composite modulus of subgrade reaction and for several modes of port pavement loads, including container stacks and loading equipment, such as front lift truck and straddle carrier. Results indicated that container stacking on the slab edge is the critical load and would require substantial strengthening of existing pavements and large investments in new ones. To overcome this problem it was decided to restrict container stacking to a minimum distance of 38 cm (15 in.) from the edge. Consequently, new pavements were designed on the basis of the loads of the container-handling equipment, and existing pavements were strengthened to meet the same criteria. A design chart was developed to assess the risk of liquefaction of loose sandy subgrade soils during future large earthquakes. The chart is based on expected ground motion levels and standard penetration test N-values. Finally, remedial measures were recommended to improve density and the liquefiable deposits in new pavement areas.

A case study of rigid pavement design is presented for the ports of Valparaiso and San Antonio located in the central region of Chile, as shown in Figure 1. A large earthquake occurred in the Pacific coast area near the ports on March 3, 1985, as reported by Poran et al. (*1,2*). The earthquake had a surface wave magnitude of $M_s = 7.8$ on the Richter scale and its intensity was rated as VII and VIII (on the modified Mercalli scale) at the Valparaiso and San Antonio ports, respectively. Both ports suffered severe damage from the earthquake. The rehabilitation plan for these ports includes the addition of substantial container-handling facilities as described in the report on development program of ports of the Fifth Region (*3*). The existing pavements in the ports are rigid. Several alternatives for new pavements were considered in a preliminary life cycle cost analysis on the basis of design criteria (*4–6*). Results of the study indicated that new rigid pavements are most economical primarily because of the operational constraints in the ports where the new facilities are also designated for general cargo.

Evaluation of existing pavements in the ports indicated that the solid and uncracked slabs are 30 cm (12 in.) thick with a modulus of elasticity of over 34 500 MPa (5 million psi) and have a flexural strength of over 4620 kPa (670 psi). The concrete slabs are supported by cement-stabilized granular base placed on high-quality compacted subbase overlying hydraulic fill that varies in thickness between 3 and 12 m (10 and 40 ft). Large-scale liquefaction was induced by the 1985 earthquake in the areas in which the hydraulic fill consisted of loose sandy soils. As a result, many existing rigid pavement areas suffered severe damage and were rendered inoperable (*2*).

Performance observations of rigid highway pavements and numerical methods (*7*) have shown that edge stresses are more critical than corner or interior stresses in pavement slabs. Experience with rigid airport pavements is similar, as reported by FAA (*8*). A computer code H51 that was developed for FAA on the basis of the work by Kreger (*9*) was used for this analysis. The program permits accurate computation of tensile stresses at the edge of a concrete slab under any local configuration. This program was used to develop the design charts and personal computer programs for most standard aircraft, including the largest 747s and DC-10s (*8*). Comprehensive design charts for port pavements were published by the British Port Association (*6*). However, these charts were not applicable for the evaluation because the existing pavement structure in Chilean ports is not included. The computer program CORNER, which is based on Westergaard's corner equations published by Ioannides et al. (*10*), was used to compute stresses in the slab corner.

Special consideration was given to improvement and densification of sandy subgrade soils for new pavement in hydraulic fill areas on the basis of a liquefaction risk evaluation procedure outlined by Seed et al. (*11,12*). The criteria are based on standard penetration test (SPT) N-values and expected peak ground acceleration (PGA) at the ports during a future large earthquake in the central region of Chile.

The results of these case studies are outlined as follows.

EXISTING PAVEMENT SYSTEMS

Design Specifications

Available design reports indicate that the existing rigid pavements at the Chilean ports of Valparaiso and San Antonio were designed to specifications similar to those for a pavement structure that consists of the following layers:

- Concrete slabs
  - –Thickness, 30 cm (12 in.);
  - –Minimum compressive strength, 36.2 MPa (5,250 psi);

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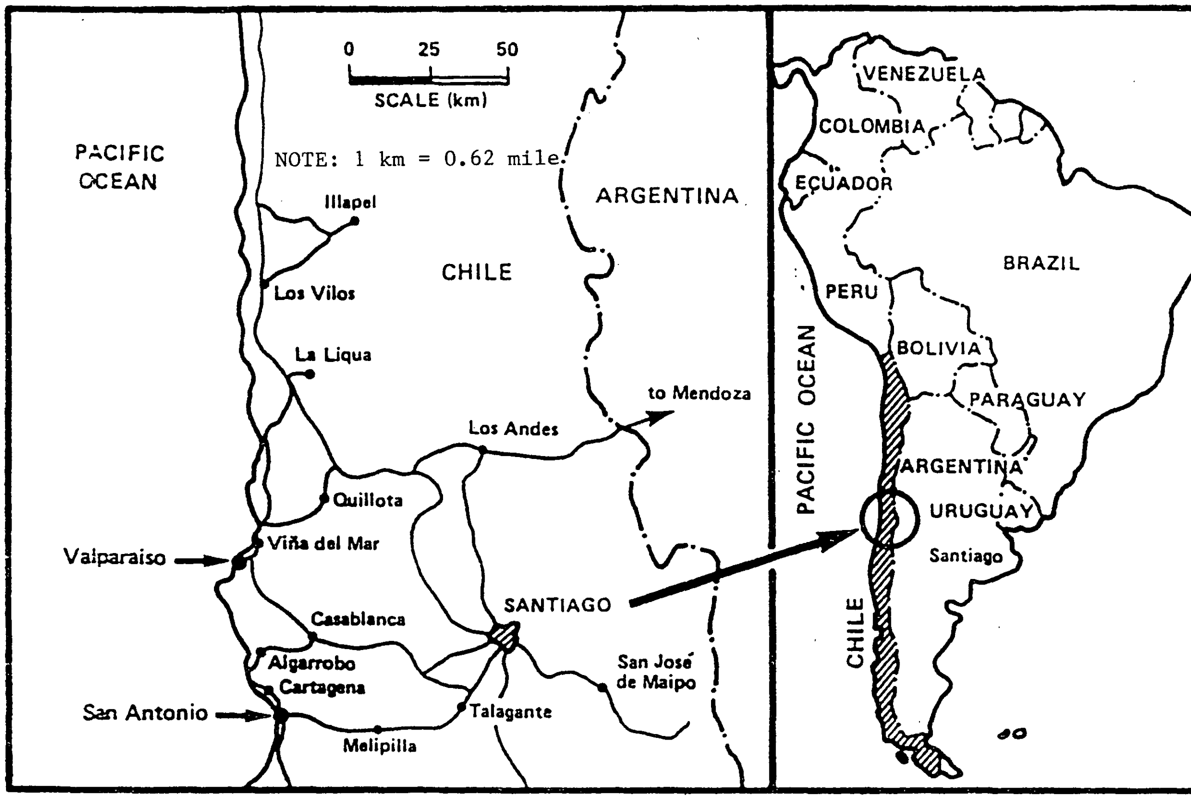

FIGURE 1 Port locations.

–Minimum flexural strength, 4590 kPa (665 psi);
–Minimum modulus of elasticity, 27 580 MPa (4×10^6 psi);
–Estimated Poisson's ratio, 0.15.

- Cement-stabilized base: The thickness of the existing cement-stabilized base (CSB) varies in different port areas between 25 and 38 cm (10 and 15 in.). The CSB was stabilized with 6 percent portland cement by weight and was required to have a minimum elastic modulus of 690 MPa (100,000 psi).
- Subbase: Under the CSB there is a high-quality subbase material 41 to 61 cm (16 to 24 in.) thick. The subbase material was required to have a minimum California bearing ratio (CBR) of 40 percent.
- Fill: The subbase overlies areas of hydraulic or local fill with thickness of 3 to 12 m (10 to 40 ft) above the natural dense granular soil deposit and bedrock (in several locations at the port of Valparaiso). Mean sea level is generally 2.8 m (9 ft) below the top of the fill.

Evaluation of Existing Pavement Systems

Nondestructive testing (NDT) based on deflection measurements can be effective in the evaluation of existing conditions of both rigid and flexible pavements, as discussed by Greenstein (*13*) and numerous other authors. Although NDT was initially considered for these ports' pavements, no such tests were conducted because of budgetary constraints. However, available plate load test results conducted on a subbase layer of a similar pavement indicated that the minimum composite subgrade reaction of subbase and fill was 200 lbf/in.^{3} These results were used for correlations (*3*). On the basis of boring logs and test results from the ports' pavements, it was concluded that the actual properties of the existing pavements were as follows:

- Concrete slabs
  –Thickness, 30 cm (12 in.);
  –Minimum flexural strength, 4620 kPa (670 psi);
  –Minimum modulus of elasticity, 34,500 MPa (5×10^6 psi).
- Cement-stabilized base: The minimum elastic modulus was estimated to be 1030 MPa (150,000 psi). Figure 2 (*14*) was used to evaluate the composite modulus of subgrade reaction for the CSB, subbase, and fill material. Using a minimum subgrade reaction modulus of 54 MN/m^3 (200 lb/in.^{3}) on the subbase, the estimated result on the CSB is 136 MN/m^3 (500 lb/in.^{3}).
- Subbase: Soil testing data indicated that the ASTM D-2487 classification of the subbase is SP-GP or SM-GM with a CBR of more than 40 percent. Test results indicated that the composite elastic modulus of the subbase and fill materials varies between 145 and 386 MPa (21,000 and 56,000 psi) and the composite modulus of subgrade reaction (k) is in the range of 54 to 95 MN/m^3 (200 to 350 lb/in.^{3}).
- Fill: Many SPT N-value profiles were compiled for the fill material and were used in the liquefaction risk evaluation as subsequently described in this paper.

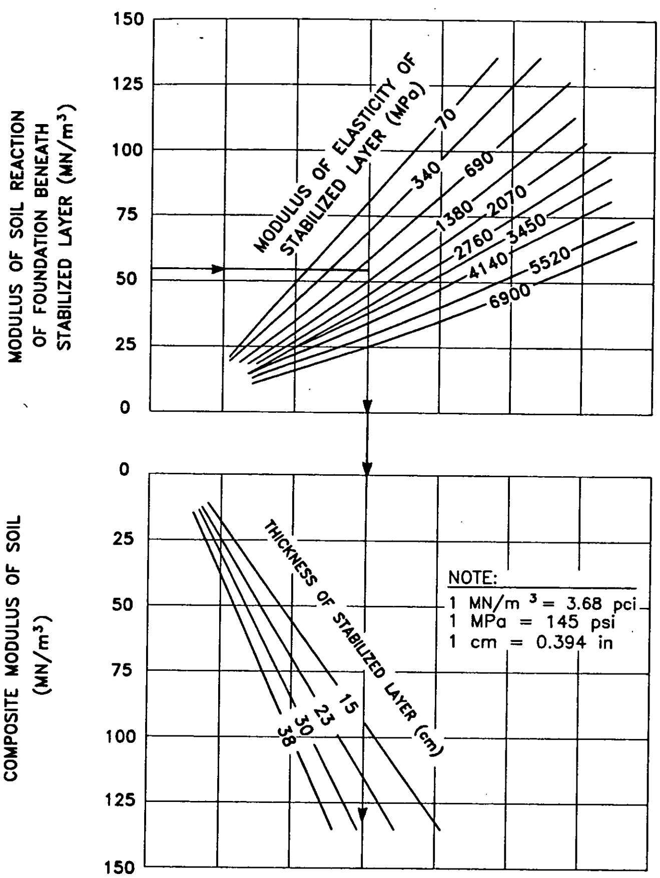

FIGURE 2 Nomogram to determine the composite subgrade reaction modulus for stabilized base overlying subgrade.

DESIGN LOADS

Design load calculations for the container stack loads and handling equipment (including dynamic factors) generally were based on the procedures outlined (*6*). The following representative loads were considered for these port pavements:

- Container stack loads: The most commonly used containers in Chilean ports are 12.2 m (40 ft) long. On the basis of Chilean statistics, a maximum weight of 214 kN (24 tons) was considered for a single container. According to the Chilean specifications, the design loads were based on stacking in three levels, one on top of the other. Therefore, the total load was 642 kN (72 tons) and the design load was reduced by 20 percent according to the design recommendations (*6*) because it is unlikely that all three containers in the stack will be fully laden. These loads are transferred to the rigid pavements through four corner supports (castings). Each support has a contact area of 289 cm² (44.8 in.²). Therefore, the design contact pressure for each support is equal to 5080 kPa (737 psi). Figure 3 shows the critical container load configuration on the slab edge. Obviously, the distance from the slab edge (X) significantly affects the tensile stresses in the slab. These stresses reach their maximum value for $X = 0$.
- Front lift truck: The front lift truck is a common type of container-handling equipment in multipurpose port facilities.

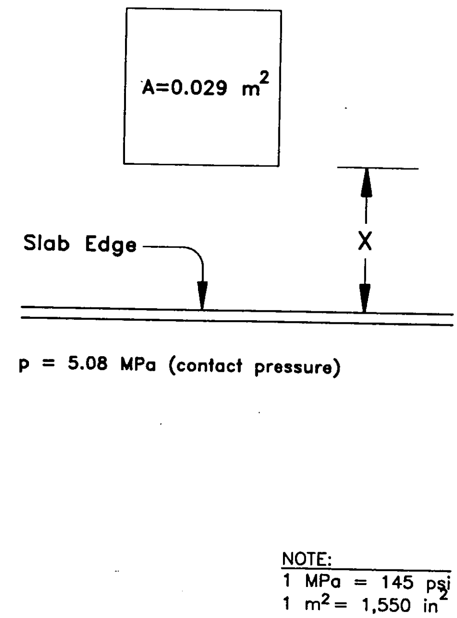

FIGURE 3 Layout of container stack castings near the slab edge.

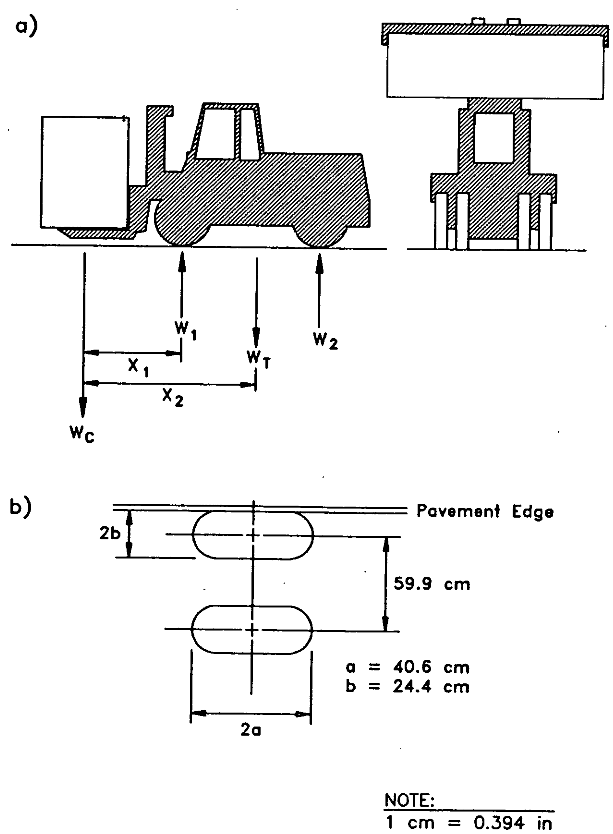

FIGURE 4 Front lift truck: *a*, dimensions and weights; *b*, critical edge loading layout.

A front lift truck is shown in Figure 4*a*. It has two dual wheels, as shown in the assembly configuration of Figure 4*b*. The critical front end design load (W_1) is distributed on two wheels; the load on each wheel is 246 kN (55,000 lb), with a contact pressure of 783 kPa (113.6 psi) and a contact area of 0.31 m^2 (484.4 $in.^2$).

- Straddle carrier: The straddle carrier, also container-handling equipment, is shown in Figure 5. Under critical operating conditions the design loads were considered for a single wheel parallel to the slab edge (the adjacent wheel has a negligible effect on these stresses) and all wheel loads are considered equal. Two different types of straddle carriers were specified with wheel loads of 195 and 342 kN (44,000 and 77,000 lb) and contact pressures of 1077 and 783 kPa (156.2 and 113.6 psi), respectively.

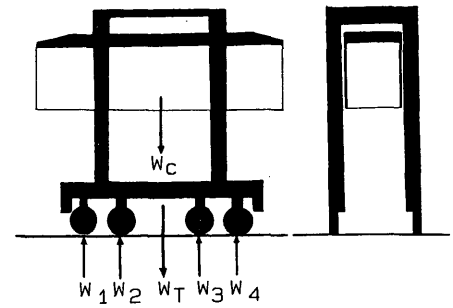

FIGURE 5 Layout of a straddle carrier and acting loads.

EVALUATION OF PAVEMENT STRESSES

The effects of various load configurations and slab thicknesses on tensile stresses in the slab were investigated for both edge and corner loading. Edge loading stresses were computed with the H51 computer code, and stresses at the slab corner were computed with the CORNER computer program, as follows.

Stresses Caused by Container Stack Loads

Figure 6 shows the relationship between the tensile stress at the slab bottom and the slab thickness for container stack loads. Lines 1A and 1B represent free edge loading for composite subgrade reaction modulus of 136 and 95 MN/m^3 (500 and 350 $lb/in.^3$). It is well established that adequately constructed joints transfer loads between the jointed slabs. According to Chilean experience this load transfer is at least 25 percent (i.e., 25 percent of the edge load is transferred to the jointed slab). Therefore it is necessary to look at 25 percent stress reduction at jointed slab edges. Line 2 represents the stress-thickness relationship for a jointed edge and *k*-value of 136 MN/m^3 (500 $lb/in.^3$). Line 3 represents the stress-thickness relationship at the corner of the slab.

On the basis of operational forecasts (*3*), 10,000 load repetitions were considered for container stacking during the design life of these pavements. On the basis of the literature (*10,15*), the allowable stress/strength ratio (SSR) for 10,000 load repetitions is 0.64. Therefore, the allowable tensile stress in the slabs is 2965 kPa (430 psi, computed as 0.64 × 670 psi). Finally, Line 2 in Figure 6 was used to determine the

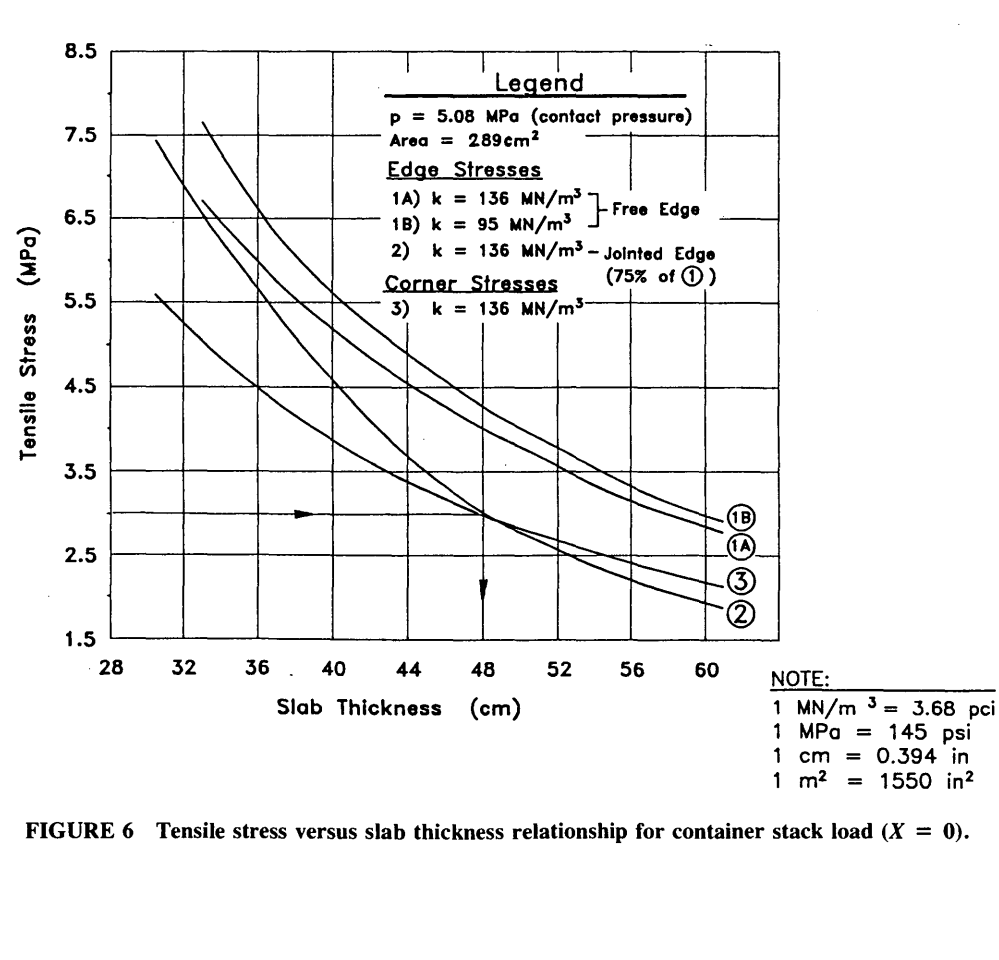

FIGURE 6 Tensile stress versus slab thickness relationship for container stack load (X = 0).

required slab thickness to support container stacks at the edge. For allowable stress of 2965 kPa (430 psi) the required slab thickness is 48 cm (19 in.). This also implied that an additional overlay concrete slab with a minimum thickness of 18 cm (7 in.) will be needed to support 10,000 repetitions of these loads provided that there is a monolithic bond between the overlay and the existing slab and that the joints overlap. In many areas of the ports the existing slabs are cracked and shattered. Based on FAA (*8*), these areas will require concrete overlays of up to 33 cm (13 in.). This requirement was rendered economically infeasible, as subsequently discussed.

Stresses Caused by Container-Handling Equipment

Figures 7 and 8 show stress-thickness relationships for front-lift truck and straddle carrier, respectively. These relationships were computed with the H51 and CORNER computer programs for edge and corner stresses, respectively.

Figure 7 clearly shows that edge stresses are much higher than corner stresses and therefore are considered critical. Based on operational forecasts (*3*), 100,000 load repetitions were considered for the front lift truck during the design life of these pavements. In this case an SSR = 0.56 was used, and therefore the allowable stress was reduced to 2586 kPa (375 psi). Finally, Line 4 was used for thickness design under front lift truck loads. This line represents 25 percent of the load transfer of the jointed slab and a composite modulus of subgrade reaction of 136 MN/m^3 (500 $lb/in.^3$). Figure 7 indicates that the required slab thickness for front lift truck operations is 45 cm (17.5 in.).

Figure 8 shows a stress-thickness relationship caused by straddle carrier operations. Again, slab edge stresses are higher than corner stresses (which were not plotted on this figure). The graph is based on the required 100,000 load repetitions for this type of equipment during the design life of the pavement (*3*). Lines 4 and 5 are used for design with the 342- and 195-kN (77,000- and 44,000-lb) wheel loads, respectively. For an allowable stress of 2965 kPa (430 psi), these lines indicate that the required slab thicknesses are 35 and 30 cm (14 and 12 in.), respectively.

DESIGN RECOMMENDATIONS

On the basis of the evaluation mentioned earlier, the design recommendations were as follows.

Container Stack Loads

The evaluation indicated that a 48-cm (19-in.) slab is needed to support the container stacks. This was previously determined for the worst case, in which the container castings are placed on the slab edge ($X = 0$). If the stacking is restricted to a certain short distance from the edge ($X > 0$), these stresses are significantly reduced. The Chilean Port Authority requested an evaluation of the alternative to restricting the

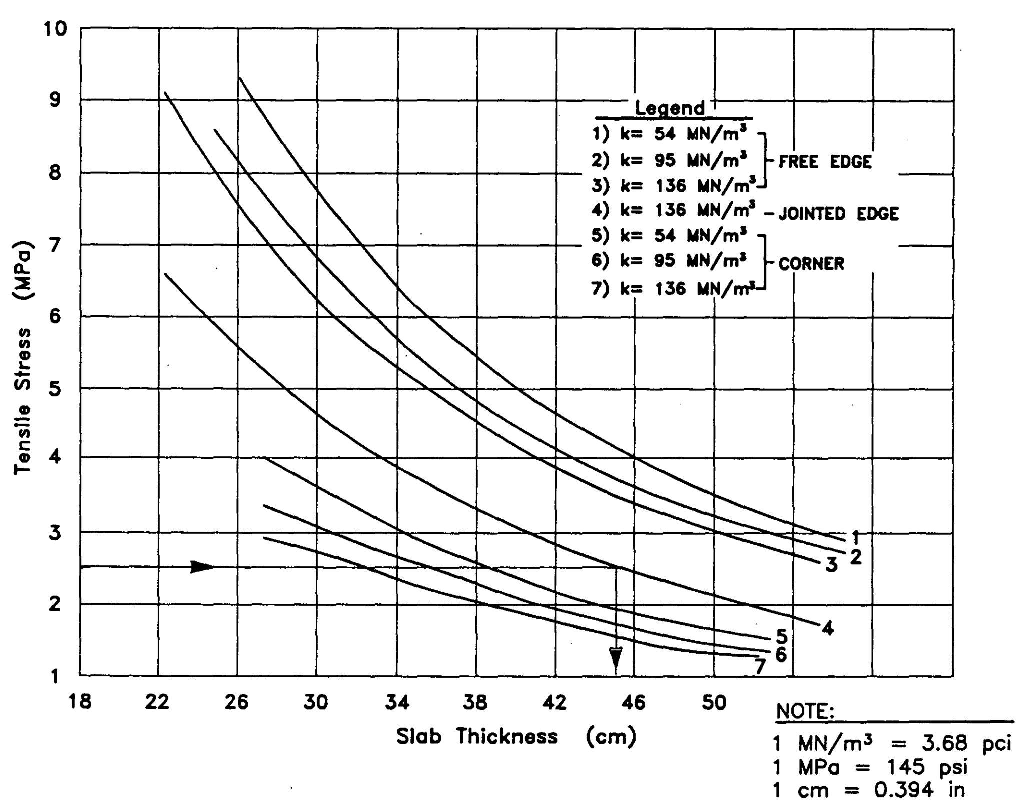

FIGURE 7 Tensile stress versus pavement thickness for front lift truck.

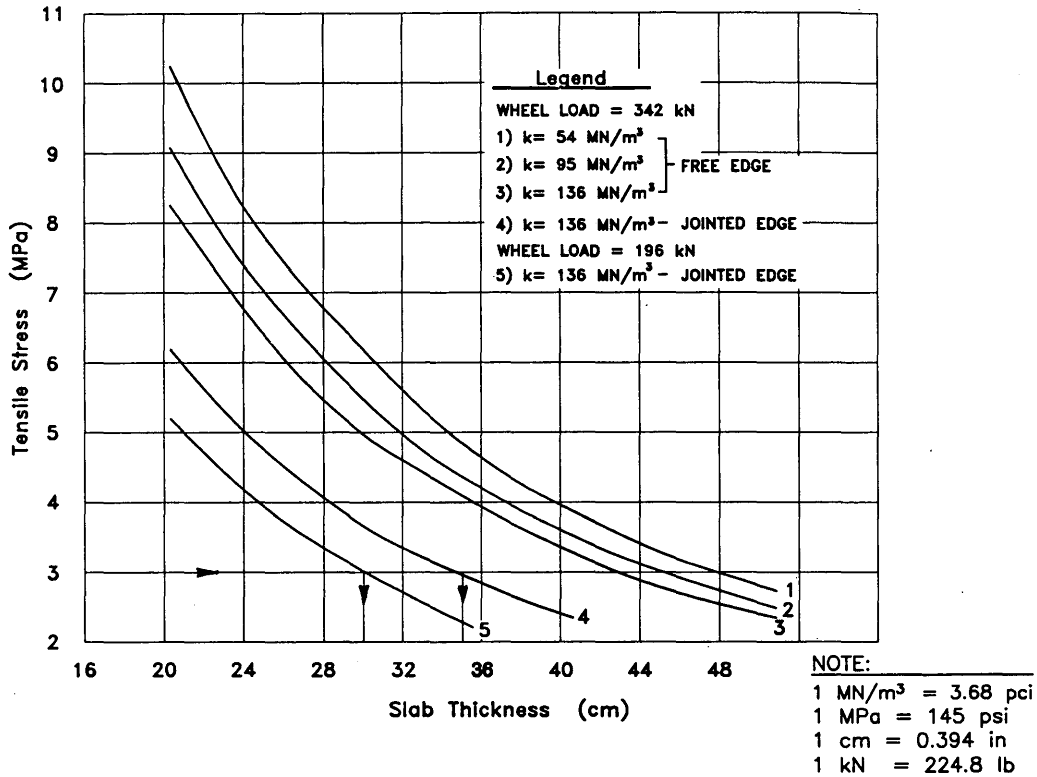

FIGURE 8 Tensile stress versus pavement thickness for straddle carrier.

container stacking at slab edges. This required that the appropriate distance (X) be determined to ensure that the edge stresses would not exceed 2965 kPa (430 psi). The H51 program was used for this evaluation, and the results are shown in Figure 9. For example, Line 3 represents the stress-thickness relationship that occurs when the container support is located 40.6 cm (16 in.) from the edge. This line yields edge tensile stresses of 2070 and 2830 kPa (300 and 410 psi) for slab thicknesses of 41 and 30 cm (16 and 12 in.), respectively. Line 1 represents the worst case ($X = 0$), in which these tensile stresses reach their maximum value. According to Figure 9, with the existing slab thickness of 30 cm (12 in.) the stresses will be equal to the allowable stress of 2965 kPa (430 psi) when the container stack is located 38 cm (15 in.) from the slab edge. The policy of controlling the container stack location was found more economical and practical than strengthening the existing pavement structure with a minimum concrete overlay of 18 cm (7 in.).

Front Lift Truck

As previously evaluated, the required slab thickness for the front lift truck is 45 cm (17.5 in.). Because this handling equipment is going to be used only in defined and channelized lanes, only a limited area needs to be strengthened (*3*). The recommendations specified that in these areas a monolithic concrete overlay of 15 cm (6 in.) be constructed on solid and uncracked existing slabs only and that the cracked and shattered slabs be replaced with new slabs 45 cm (17.5 in.) thick.

Straddle Carrier

No strengthening was recommended for the areas in which the lighter equipment is used [195 kN (44,000 lb) per wheel load]; the uncracked slabs 30 cm (12 in.) thick were judged adequate. On the other hand, it will be necessary to construct an 8-cm (3-in.) monolithic concrete overlay for the straddle carrier with a load of 342 kN (77,000 lb) per wheel (based on a minimum overlay thickness) and construct slabs 35 cm (14 in.) thick for the new pavement.

EARTHQUAKE CONSIDERATIONS

The massive earthquake that took place on March 3, 1985, in the central region of Chile had a surface wave magnitude of $M_s = 7.8$ on the Richter scale. Its epicenter was located in the Pacific Ocean approximately 39 km (24 mi) from the port of San Antonio. The earthquake intensity was rated as VII and VIII on the modified Mercalli scale at the ports of Valparaiso and San Antonio, respectively. The damage to the port facilities was extensive (*3*). Large settlements occurred in backfill and pavement areas where loose sandy deposits liquefied and some existing pavement areas were destroyed.

Liquefaction risk analysis was conducted on the basis of the procedure described previously (*11,12*), and the results are presented in Figure 10. The critical envelope shown is a convenient method for evaluating liquefaction potential based on SPT N-values for a large number of soil borings performed in the sandy hydraulic fill deposits before and after the earth-

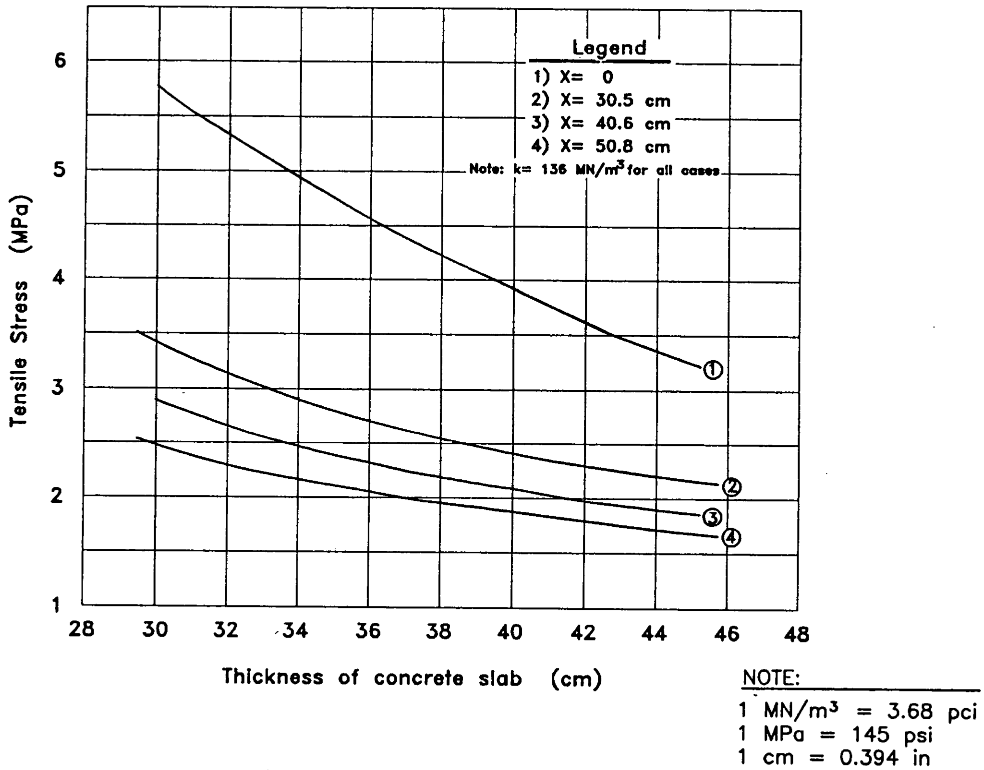

FIGURE 9 Stress-thickness relationship of a jointed edge for container stack load.

quake. The limits indicated are based on the range of PGA values recorded at the port of San Antonio during the March 3, 1985, earthquake (*1,2*). The earthquake design considered for the ports is expected to result in PGA values within this critical range. The range shown on the left side of Figure 10 is the lower limit. It corresponds to sandy soils in which liquefaction is likely to occur. The range located between the two limits is defined as the critical range or the zone of uncertainty. This critical range corresponds to PGA values of 0.67 and 0.43 g for the upper and lower limits, respectively. The upper limit may be applied to sandy soils with D_{50} larger than 0.25 mm (0.01 in.), and the lower limit may be better suited for silty sands with 15 percent fines.

The upper limit in Figure 10 was recommended as the design curve for the minimum required density of the fill material under water level. In the Chilean ports the water level is approximately 3.95 m (13 ft) from the ground surface. For example, at a depth of 4.5 and 9 m (15 and 30 ft) from ground surface, the SPT *N*-value should be a minimum of 30 and 40, respectively, to resist liquefaction during an earthquake similar to the one in 1985.

These criteria are recommended for hydraulic fill deposits under water level in new rigid pavement areas and in areas in which existing pavements were badly damaged from liquefaction induced by the 1985 earthquake. The damaged pavements will be reconstructed to the new specifications. Dynamic compaction, sand piles, or vibroflotation were recommended as effective soil improvement methods for these loose sandy deposits (*3*) to mitigate the risk of liquefaction.

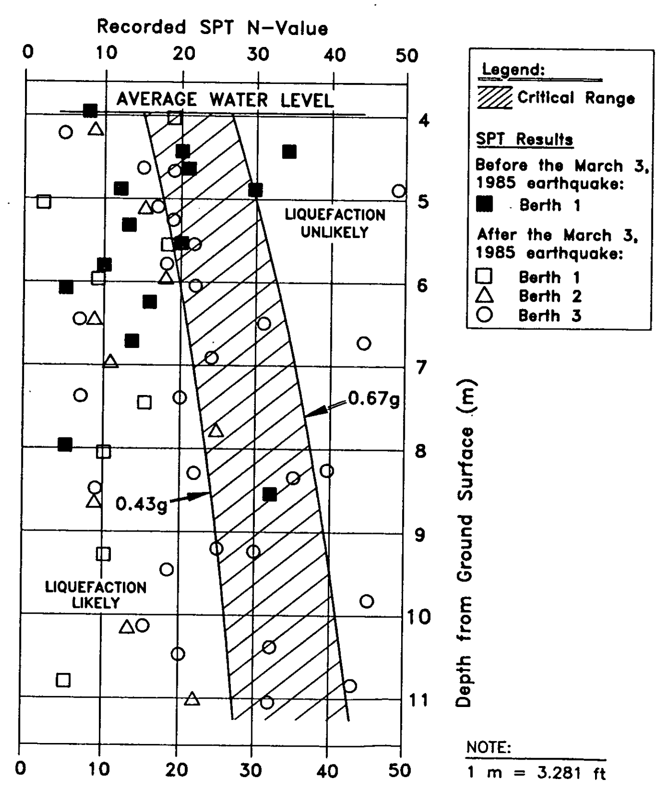

FIGURE 10 Critical liquefaction range for sandy soils in the Port of San Antonio.

In addition, it was shown (*2*) that loose sandy fill above the water level may also undergo considerable settlement during strong earthquakes. Therefore, it was recommended that the fill material above water level be compacted to a minimum of 95 percent of AASHTO-T 99-90.

SUMMARY AND CONCLUSIONS

1. A rational methodology for rigid pavement design was developed for the Chilean Port Authority. Tensile stress-thickness relationships were computed at slab edge and corner for various levels of composite modulus of subgrade reaction and representative loads associated with container operations. Two computer programs were used for this evaluation. Generally, it was concluded that edge loading governs pavement thickness.

2. The representative design loads used in this analysis were container stack castings, front lift truck, and straddle carrier. The loads were computed on the basis of Chilean specifications with the procedures outlined (*6*). A total load of 514 kN (58 tons) was used for a stack of three containers with contact pressure of 5080 kPa (737 psi) and a contact area of 289 cm^2 (44.8 $in.^2$). The front lift truck was considered with two dual wheel assemblies, a wheel load of 246 kN (55,000 lb), and contact pressure of 783 kPa (113.6 psi). Two types of straddle carriers were considered with wheel loads of 195 and 342 kN (44,000 and 77,000 lb) and contact pressure of 1077 and 783 kPa (156.2 and 113.6 psi), respectively.

3. Design charts of required slab thickness that are based on load repetitions during the design life are presented. It was concluded that a slab 30 cm (12 in.) thick is adequate if the container stacking areas are arranged in such a way that the castings are restricted to a minimum distance of 38 cm (15 in.) from the edges of the slabs. This arrangement will result in substantial savings in the new pavement areas and will not require overlays on the existing ones. A rigid pavement 45 cm (17.5 in.) thick will be required in the channelized areas of front lift truck operations. The straddle carrier with a 195-kN (44,000-lb) wheel load will require slabs 30 cm (12 in.) thick. However, the heavier straddle carrier with 342-kN (77,000-lb) wheel load will require a minimum overlay of 8 cm (3 in.) on existing slabs, for a total of 38 cm (15 in.), and a thickness of 35 cm (14 in.) for new pavements.

4. Deep soil improvement and densification were recommended to minimize liquefaction settlements and pavement failures. The liquefaction risk evaluation procedure is based on SPT *N*-values. For the pavement areas, a minimum *N*-value is specified for any given depth of the sandy fill material below water level. Dynamic compaction, vibroflotation, or sand piles were recommended for deep soil improvement. Conventional compaction was also recommended to minimize subgrade settlement of loose sandy soils above water level.

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