deterioration in the low-salt regions of the South and West are used instead, one would expect only about 5 percent, or approximately 3,000, to be damaged (Table 3-5).

This rough calculation suggests that about 7,000 decks (10,000 − 3,000) will become damaged during the next 10 years because of continued salting. As a practical matter, however, future deck damage will probably be less severe than past rates of deterioration suggest, mainly because of recent advances in bridge deck protection (discussed in the next section). Because of these advances, it is reasonable to assume that 7,000 is the high end of the range, and that about half this number is the low end.

To estimate the average annual cost of repairing damaged decks, it can be assumed for simplicity that about 1 in 10, or 350 to 700, will need to be rehabilitated each year during the 10-year period. The typical surface area of a deck is 7,000 ft^2 (Table 3-5). Multiplication of this average by 350 to 700 decks yields between 2.5 million and 5 million ft^2 that will need to be rehabilitated each year. According to estimates by the California and New York State highway departments, the average cost of rehabilitating a concrete deck, whereby the concrete is replaced and the rebars are cleaned, is between \$20/ft^2 and \$40/ft^2 (personal communications, Structures Division, New York State Department of Transportation and Office of Transportation Materials and Research, California Department of Transportation). Multiplication of this cost range by the 2.5 million to 5 million ft^2 that would need to be repaired each year results in a repair cost of between \$50 million and \$200 million per year.

Bridge Deck Protection

The premature deterioration of concrete decks during the past 20 years challenged highway agencies not only to save the thousands of decks that were already critically contaminated with chloride but also to design and construct more durable decks that are resistant to salt-induced corrosion. Because bridge decks are complex systems, the challenge involved many elements of the deck, ranging from improved deck drainage and joint sealants to special deck overlays that impede migration of chlorides into the concrete.

Since 1984, FHWA has required protections on all new federal-aid bridges in salt-using states. The types of protections used, however, vary among states, depending on individual needs and the performance and cost of each type. In the survey of state highway agencies conducted for this study, 40 of 48 responding states reported that they routinely use some type of protective system on bridges built where road salt is used. By far the most common is epoxy-coated reinforcing steel, the use of which is standard in 25 states. Other types of protection range from waterproof membranes and special deck overlays to additional concrete cover over the reinforcing steel. Of the 25 states that routinely use epoxy-coated steel, 18 combine it with a waterproof membrane, additional concrete cover, a special deck overlay, or other protective systems.

The cost of installing and maintaining various protective systems has been studied by the National Cooperative Highway Research Program (NCHRP) (Babaei and Hawkins 1987). According to that study, epoxy-coated steel combined with a special deck overlay is the most expensive, costing about \$5.50/ft^2 more to install than a basic unprotected deck (Table 3-6). The least expensive is an additional 2 in. of concrete cover, which adds about \$2.15/ft^2 to new deck construction costs. The average incremental cost of these alternatives is about \$4/ft^2 more than a basic concrete deck.

This average is useful for quantifying the future cost of protecting newly constructed decks. An analysis of National Bridge Inventory file data indicates that between 3,000 and 4,000 new decks, with a total surface area of 20 million to 30 million ft^2, are constructed each year in salt-using regions of the United States (where deck protection is mandatory). Given an average incremental cost of deck protection of \$4/ft^2, the total cost is \$75 million to \$125 million per year (\$4/ft^2

TABLE 3-6 INCREMENTAL COST OF VARIOUS BRIDGE DECK PROTECTION SYSTEMS (Babaei and Hawkins 1987, 53)

Alternative	Additional Cost[a] (\$/ft^2)
1. Basic deck (no protection)	–
Single Protection	
2. Additional 2 in. of concrete cover	2.15
3. Epoxy-coated top rebar mat	2.60
4. 1.5 in. of latex or 2.0 in. of low-slump concrete cover	4.85
5. Additional 0.5 in. of concrete cover, plus asphaltic concrete membrane	4.40
Double Protection	
6. Alternative 3, plus epoxy-coated bottom rebar mat	3.25
7. Alternative 4, plus epoxy-coated top mat	5.50
8. Alternative 5, plus epoxy-coated top mat	5.20
Average	4.00

[a] Original 1986 cost estimates were updated for inflation.

cost × 20 million to 30 million ft^2 of deck surface, rounded to the nearest $25 million).

OTHER BRIDGE COMPONENTS

Much of the research that has been devoted to developing methods for repairing and protecting bridges from salt damage has focused on concrete bridge decks. Road salt, however, also contributes to the deterioration of other bridge components, including grid decks, joints, drainage systems, and elements of the bridge structural system that are exposed to salt from leaky decks, faulty drainage, and splash and spray from the roadway.

Grid Decks, Joints, and Drainage Systems

In addition to its use in reinforced concrete, steel is the primary material in various other components of the deck system, including grid decks, joint devices, and drainage systems. These components are vulnerable to corrosion from road salt, but numerous other factors affect their durability as well.

Most steel decks are made of grid mesh, which accounts for about 5 percent of all deck surfaces. Grid decks provide drainage of water, dirt, debris, and road salt through the grid openings. Most older grid decks have a framework of steel beams and stringers to support the mesh panels. Salt-laden snow, mud, sand, and other debris tracked onto the deck often drop onto the supporting structures, causing corrosion. Accordingly, grid decks and their supports must be regularly cleaned and painted as a precaution against rusting, which can be exacerbated by road salt (AASHTO 1976, 35–46).

Joint devices, likewise, require vigilant maintenance. Joints allow for movements of the deck caused by traffic loadings and thermal expansion and contraction. They are often made of metal formed into finger bars or plates and are therefore susceptible to rusting, especially if they are improperly sealed and become clogged with debris containing moisture and salt (AASHTO 1976, 89–126). Rusted joints that do not perform properly can generate stresses on the deck that result in pavement fracturing or cracking of the bridge approach slab. Road salt is therefore a factor that can affect joint corrosion and durability.

Like joints, deck drainage systems require frequent maintenance. The drainage system is vital to the bridge because it eliminates trapped or ponded water, which can be hazardous to traffic and contribute to deterioration of the bridge understructure. Most drainage systems use metal pipes that funnel water from the deck to the ground. Poor drainage is usually caused by debris clogging the pipes (AASHTO 1976, 61–66). When drainage systems fail, backed-up water, which may be contaminated with salt, can corrode the pipes and reach the bridge's structural system.

Structural Components

Bridge structural components vary according to bridge design, but usually include superstructure members, such as girders, stringers, and arches, which support vertical loads; substructure members, such as abutments and piers, which transmit loads from the superstructure to the ground; and bearings, which transmit loads from the superstructure to the substructure while allowing the bridge to undergo necessary movements without harmful stress. Most bridge structural elements are made of steel, reinforced concrete, or prestressed concrete, which, if exposed to road salt, are vulnerable to corrosion damage.

Bearings

Bearings serve an important function by allowing structural elements to undergo stress movements without damage. Bearings are often located where the superstructure (e.g., girders) and the substructure (e.g., pile caps) meet. Most bearing devices are constructed of steel, neoprene, bronze, or a combination of these materials (AASHTO 1976, 171–182). The steel portions of bearings are normally protected by paint or galvanization. However, sand, dirt, debris, and road salt often accumulate around the bearings, which can encourage corrosion and "freezing" of the bearing, especially if the protective system is poorly maintained.

Steel Framing and Supports

Corrosion is a problem for most steel frames and supports (AASHTO 1976, 127–199). The corrosive action of atmospheric pollutants, sea spray, and moisture all make regular cleaning and painting of steel necessary in most regions of the country. Corrosion of steel is usually detected before it becomes a serious hazard. Repairs are made by removing the rust and applying a protective paint or coating or by replacing the rusted steel section with metal plating. Corrosion is accelerated by dirt, debris, and moisture that become trapped in pockets and crevices created by the framing and connection of steel members. The addition of salt to this environment increases the potential for more frequent and severe corrosion, especially if bridge cleaning and painting are lax.

Concrete Support Structures

Road salt is frequently associated with deterioration of bridge structural elements made of reinforced concrete (AASHTO 1976, 61–66). The problem is similar to that of concrete decks; chlorides from road salt, along with moisture, migrate to the rebars, inducing corrosion and causing the surrounding concrete to crack (Figure 3-6). Reinforced concrete box beams, stringers, pile caps, and support columns are among the structural elements affected. Leaky joints, poor drainage, and splash and spray from traffic provide avenues for salt access.

Because road salt is not applied directly to these elements, salt damage takes longer to be identified and is generally not as extensive as salt-induced damage to decks. However, because of cramped working conditions and the need for falsework and scaffolding, repair of even minor damage can be difficult and expensive. Research is under way to develop less costly repair and rehabilitation treatments, such as electrochemical chloride removal (Broomfield and Jawed 1990; Manning and Schell 1987; Manning and Pianca 1991). These treatments, along with greater attention to deck drainage and corrosion protection (such as epoxy-coated steel) should help reduce the severity and incidence of this damage. Nevertheless, because rehabilitation of the structural components of one long-span bridge can cost several million dollars (personal communication, Structure Division, New York State Department of Transportation), the total cost of salt-related damage is likely to be quite high.

Prestressed Concrete

There is some evidence that long-term exposure to road salt can damage prestressed concrete used for structural support. Prestressing improves the strength of bridge structural components by the ten-

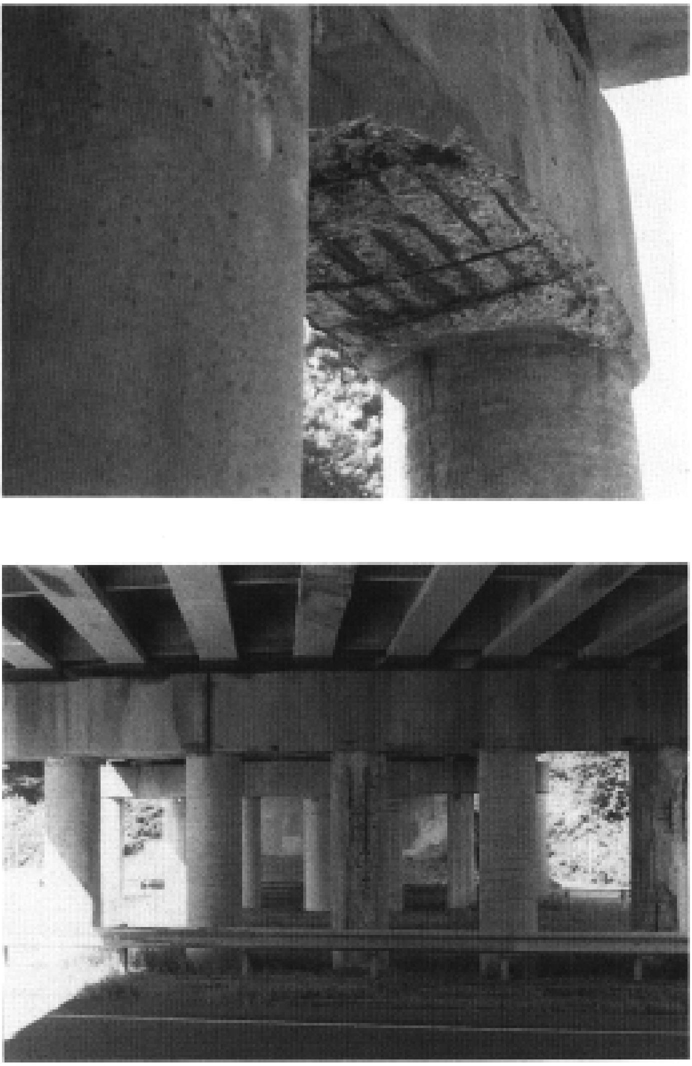

FIGURE 3-6 Concrete spalling on bridge structure.

sioning of steel strands in the concrete. Because several prestressed segments can be strung together with minimal intermediate support, this design is popular for long-span bridges crossing stretches of rough terrain, bodies of water, and congested urban areas. Because the steel strands are vital to structural integrity, the consequences of corrosion are far greater than corrosion of rebars.

According to the National Bridge Inventory, there are about 25,000 prestressed bridges in the United States, accounting for about 5 percent of all bridges. To date, surveys of the condition of these bridges have found few corrosion-related problems. More than 12,000 prestressed concrete bridges were built in the United States between 1951 and 1966. According to an NCHRP study, highway agencies in 14 states that collectively contain more than half of these bridges report no widespread problems (Perenchio et al. 1989, 5). In addition, a survey conducted by the American Concrete Institute found that of more than 30 million strands installed between 1950 and 1977, only 200 were affected by corrosion, usually due to corrosive environments involving seawater, poor design details, or faulty construction (Shupack 1978). Prestressed concrete has been known to fracture and fail due to hydrogen embrittlement and stress corrosion, although reported instances of this type of damage are rare and usually unrelated to road salt use (Perenchio et al. 1989, 5).

The sudden collapse of a 30-year-old prestressed concrete bridge in the United Kingdom in 1985, which was attributed to road salt–induced corrosion, renewed debate about the potential for salt-induced corrosion of prestressed concrete bridges (Woodward 1989). Of particular concern is that corrosion of prestressing strands may take several decades to occur, because the strands are often embedded in grout or special ducts. Most prestressed concrete bridges are relatively new, constructed during the past 35 years. Corrosion protection in many of these structures was provided by the use of high-quality construction materials and additional concrete cover. Because of the potentially catastrophic consequences of corrosion, most highway agencies now take extra precautions by coating and protecting the strands, ducts, and anchoring hardware in new bridges (Perenchio et al. 1989, 2–3).

Because of the uncertain effect of road salt on prestressed concrete bridges, cost projections would be speculative. The only cost that can clearly be associated with salt use is that of corrosion protection and detection activities. However, should significant corrosion of prestressed concrete bridges eventually be discovered, the total cost would be considerably higher.

Summary of Impacts on Other Bridge Components

In addition to decks, components of bridges that are vulnerable to salt damage include concrete supports, steel framing, bearings, and joint devices. The effects of salt on these components are frequently obscured by durability and maintenance factors unrelated to salt use. Salt can reach these components because of leaky decks, faulty drainage, and splash and spray from the roadway. Compared with deck damage, however, deterioration of other bridge components can be more expensive and difficult to repair, especially if it involves structural support elements. Although there is not enough information available to estimate costs reliably, the committee believes that collectively they are as large as deck costs and, as a rough approximation, fall within the same range, $125 million to $325 million per year.

OTHER HIGHWAY COMPONENTS

Road salt is clearly a principal factor in bridge durability. Its impacts on other highway system components, including pavements, drainage systems, and roadside fixtures and appurtenances, are more incremental and difficult to isolate.

Pavements

Pavements (both concrete and asphalt) are the single most expensive component of the highway system, accounting for about one-fifth of all highway expenditures (TRB 1984, 64). In recent years, interest in reducing these expenditures has generated considerable research aimed at improving pavement designs, materials, and maintenance practices. However, the impact of road salt is not an area of major concern or research.

Perhaps the best-known effect of road salt on pavements is its aggravating effect on surface scaling, or flaking, in poor-quality portland cement concrete. When improperly cured, overfinished, or inadequately entrained with air—whereby microscopic air bubbles are mixed in with the concrete—concrete pavement is vulnerable to stress damage caused by trapped moisture that freezes and expands.

Road salt can exacerbate this problem, both by increasing freeze-thaw cycles and by forming expanding crystals in the concrete. This effect is no longer a serious concern for most highway agencies, however, because air entrainment has been a standard construction practice for many years.

A more practical concern is the performance and durability of pavement expansion joints. Expansion joints are constructed in concrete pavement to control stresses. The joints themselves, however, require considerable maintenance. Cracks in jointed pavements are sometimes caused by corrosion of steel dowels that are installed in the joint. The purpose of these devices is to transfer loads across joints while allowing the joints to open and close freely in response to slab movements. When these devices corrode, however, they may restrain joint movement, resulting in slab faulting and cracking. The use of road salt is a factor considered by highway agencies when they select metals and coatings used in joint devices (TRB 1979, 12). Yet, because joints are sometimes unsealed and exposed to numerous other corrosion sources—such as moisture, dirt, and debris—it is difficult to attribute a portion of this damage to road salt.

The corrosion of the reinforcing steel sometimes used in concrete pavements is another potential effect of salt. According to the Concrete Reinforcing Steel Institute, there are about 30,000 lane-mi of reinforced pavement in the United States, mostly on freeways and other heavily traveled highways (Concrete Reinforcing Steel Institute 1983, 1). Reinforcing steel eliminates the need for joint devices and provides additional concrete tensile strength. Like decks, reinforced pavements are susceptible to spalling and cracking caused by rebar corrosion. Overall, however, the extent and severity of this damage does not approach that of bridge decks, and the general condition of these pavements is thought to be well within the normal bounds for pavements serving high volumes of traffic (TRB 1979). During the 1970s, several incidents of severe spalling of pavements were linked to the use of deicing salt in Minnesota (TRB 1979, 10). Few serious problems have been reported since that time, although some northern states (e.g., Wisconsin) are using epoxy-coated rebars in new concrete pavements.

Highway Drainage Systems

Some of the salt spread on highways is washed through highway drainage and storm sewer systems, consisting of reinforced concrete culverts, metal pipes, catch basins, grates, manhole covers, curbs, and gutters. Because drainage systems account for about 10 percent of highway construction and maintenance expenditures and are important to highway operations and safety, their performance and durability are critical (TRB 1978, 3).

A deteriorating drainage system can be difficult and expensive to repair. Treatments, such as retrofitting coatings and linings to pipes, are often costly and conflict with the original design objectives of the structure (TRB 1978, 23). Hence, as a precaution, new culvert pipes are often equipped with thicker walls, galvanized coatings, and protective paving materials. In addition, to prevent scaling and cracking of curbs and grate spacers due to freeze-thaw effects, air-entrained concrete and stone are used in new construction.

Although high concentrations of road salt can enter highway drainage systems after storms, the water flow usually causes dilution. High chloride concentrations over a long period may accelerate the corrosion of drainage pipes by interfering with the formation of natural protective films on pipe surfaces and by increasing the conductivity of draining water (Bednar 1989, 70). In addition, salt may contribute to scaling and cracking in improperly cured or finished concrete grout, curbs, and grate spacers by aggravating freeze-thaw effects. In general, however, salt is not considered a significant factor affecting the durability of drainage systems. During the past 30 years, several states have studied the performance of highway drainage systems. The studies have led highway agencies to conclude that the factors with the greatest effect on durability are soil type, water alkalinity and hardness, traffic stress and vibration, silting, road settlement, erosion, and water abrasion (TRB 1979; Bednar 1989, 70–71).

Highway Fixtures and Appurtenances

Signposts, light columns, circuitry in traffic signals, guardrails, wire fencing, retaining walls and noise barriers, as well as their concrete bases and connection hardware, are vulnerable to damage from road salt. Many highway fixtures and appurtenances are specially painted or constructed with corrosion-resistant materials. For example, wiring and fences are made of galvanized steel, light and sign supports are constructed of aluminum alloy tubing and anchored with stainless steel bolts, and guardrails are often painted with zinc-rich primer (American Public Works Association 1985). However, in general, the factors with the most effect on the maintenance and replacement schedules of these components are normal wear, vehicle collisions,