Benefits of Using Half-Cell Potential Measurements in Condition Surveys of Concrete Bridge Decks

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The benefits of using half-cell potential measurements in condition surveys of concrete bridge decks were examined using data collected from several decks by visual inspection, sounding with chain draggings, and measurement of half-cell potentials. Half-cell potentials on a deck were found to fluctuate from survey to survey, likely in response to seasonal fluctuations of temperature, oxygen, chloride, and moisture content in the concrete. Consequently, in contrast to ASTM interpretation guidelines (ASTM C-876), the numerical value of each measured half-cell potential by itself would be a poor indicator of the condition of rebars. Instead, the potential measured at each location should be considered relative to potentials measured in the surrounding concrete. When the potentials were plotted on an iso-potential contour map, the locations of active rebar corrosion and corrosion-induced damage in the concrete were associated with high negative potential gradients. Because of the localized nature of rebar corrosion, the recommended grid spacing of 4.0 ft (ASTM C-876) for surveys of bridge decks was found to be too large to allow location of existing active corrosion and the associated damage to concrete. It was determined that a grid spacing of no more than 2.0 ft should be used. If a half-cell potential survey is performed on a sufficiently small grid and the collected measurements are plotted on contour maps of iso-potential lines, the locations of existing active rebar corrosion and corrosion-induced damage in the concrete will be indicated with a high degree of accuracy by areas of relatively high potential gradients. When combined with the other inspection techniques, such a survey would be extremely useful in estimating necessary repair.

Because concrete deterioration resulting from corrosion of embedded rebars is the primary cause of premature deterioration of concrete bridge decks in many states (including Virginia), relevant deck conditions (such as cracking, spalling, delamination, chloride content in the concrete, condition of the rebars, and thickness of the concrete cover over the top-mat rebars) are given considerable attention in bridge deck surveys. Therefore, in addition to visual inspection, other inspection methods (such as sounding with chain dragging for delamination, use of a pachometer, measurement of half-cell potentials, and chemical analysis of extracted concrete samples for chloride contents) are routinely used in detailed condition surveys.

Because these inspection methods require many hours to complete, the adequacy and relevancy of each method must be reexamined whenever warranted. Different concerns are associated with the adequacy and relevancy of each of these inspection methods. Consequently, with the exception of half-cell potential surveys, various efforts have been made to either replace or improve existing methods.

Visual inspection is not quantitative and is tedious, time-consuming, and disruptive to traffic. Research efforts that may lead to its partial replacement have included the use of light-dependent resistors in measuring the width of cracks on concrete surfaces (*1*) and the development of image-processing algorithms for the analysis of the imagery of cracks in concrete surfaces (*2*).

Users have similar concerns with sounding to detect concrete delaminations. To replace it, the use of infrared thermography (*3,4*), short-pulse radar (*5,6*), and impact-echo (*7*) techniques have been reported.

The standard AASHTO method for chloride analysis (AASHTO T-260) is based on a potentiometric titration procedure developed by Berman (*8*) and improved by others (*9*). The method is destructive and expensive because the procedures involved are lengthy and require powdered samples from the deck. To reduce its cost by simplifying the analysis, shortcut procedures based on the same potentiometric approach have been attempted (*10,11*). Unfortunately, all of these procedures require reliance on a proper calibration curve because of adverse solution matrix effects on the potentiometric readings of the sample solutions. In addition, these procedures still require powdered samples from a deck.

The coexistence of corroding areas (or anodic half-cells) and noncorroding areas (or cathodic half-cells) on rebars is reflected in potential differences, or voltages, across the steel-concrete interfaces. These potentials can be measured relative to a constant reference potential provided by a suitable reference electrode. Accordingly, any change in the potential between the reference electrode and the steel-concrete interface can be attributed to, among other things, the corrosion activity at the surface of the steel.

The standard method for measurement of half-cell potentials in concrete (ASTM C-876) is based on a procedure developed by Stratful (*12*). In this method, the half-cell potential of the rebar in concrete is measured by a high-impedance voltmeter connected between the rebar network and a Cu/$CuSO_4$ reference electrode that is in contact with the surface of the concrete. To survey an entire structure, this measurement is repeated by moving the electrode to other locations or points following a grid pattern on the concrete surface. The standard procedure noted that a 4.0-ft grid spacing has

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been found to be generally satisfactory for bridge decks and that larger spacings increase the probability that localized corrosion areas will not be detected.

Based on data by Stratful et al. (*13*) obtained from surveying bridge decks and those from a laboratory study by Clear and Hay (*14*), the following guidelines are suggested for interpretation of data (ASTM C-876):

1. If potentials over an area are greater than −0.20 V, the probability that no steel corrosion is occurring in the area at the time of measurement is greater than 90 percent.
2. If potentials are in the range of −0.20 to −0.35 V, corrosion activity of the steel in the area is uncertain.
3. If potentials are less than −0.35 V, the probability that steel corrosion is occurring in the area at the time of measurement is greater than 90 percent.

This indicates that there is significant uncertainty in the relationship between half-cell potentials and the condition of rebars. This uncertainty has created doubts among bridge engineers concerning the benefits of using half-cell potential surveys to rank deck repairs and prepare repair plans where the ability to delineate and quantify the amount of needed repair, instead of predicting the probability of rebar corrosion occurring at each location, is desirable. The researchers believe that the uncertainty arose from the constant fluctuation of potential at any location with time, which has been reported recently (*15*), in response to the changing dynamics of the corrosion processes with seasonal fluctuations in the physical properties of concrete.

PURPOSE AND SCOPE

Because the half-cell potential survey procedure is so simple, inexpensive, and nondestructive, the researchers believed it worthwhile to reexamine the relationship between half-cell potential and condition of the rebar and concrete and to determine if the uncertainty could be resolved so that potential surveys could be used to locate and quantify deteriorated rebars and concrete.

Another aspect that warranted reexamination was the adequateness of the 4.0-ft grid spacing suggested by ASTM (ASTM C-876). It is likely that this spacing is so large that a significant percentage of corrosion-affected concrete areas go undetected. This may have at least partially contributed to the reports of mixed success obtained from the results of using half-cell potential surveys.

To address these issues, the researchers collected data from several concrete bridge decks, using various inspection methods, and analyzed them. The collection and analysis of these data is discussed here.

EXPERIMENTAL PROCEDURES

Five concrete bridge decks were surveyed in this study. During each survey, a preliminary sounding was conducted to allow selection of a survey area that included numerous delaminated areas. A square grid of either 1.0-ft or 2.5-ft spacing was then marked on the selected area for detailed inspection using various inspection methods.

Visible concrete distresses, such as cracks (especially those above the transverse rebars) and spalls, were recorded and carefully mapped to within 2 in. Sounding was used to detect concrete delaminations, which were similarly mapped to within 2 in.

The measurement of half-cell potentials was facilitated by use of a multiple half-cell array, which consisted of an array of four $Cu/CuSO_4$ electrodes. Depending on the grid spacing to be used in a survey, the electrodes were spaced 1.0 to 2.5 ft apart on a metal mounting bar, which was equipped with a wheel at each end to facilitate movement on the deck. A battery-powered portable data logger (Polycorder 700), which was preprogrammed to serve as a digital voltmeter (with a resolution of 1 mV), was used in conjunction with the half-cell array to store automatically, throughout each survey, all potential readings from the four electrodes. The stored data were then subsequently downloaded to a desktop computer for iso-potential contour mapping and statistical analysis using an appropriate graphic software.

DISCUSSION OF RESULTS

Half-Cell Potentials and Concrete Condition

The half-cell potentials obtained from all study areas were correlated with the condition of the concrete. To allow such correlation, it was necessary first to classify a concrete as either sound or deteriorated, on the basis of a criterion that the researchers believed reasonably conformed to the manner with which deteriorated concrete would be removed and repaired in a concrete deck. Accordingly, a concrete was classified as sound if there was no transverse crack, delamination, or spall within 6 in. of the point of measurement of half-cell potential; otherwise, the concrete was classified as deteriorated. Afterward, all the potential readings (approximately 2,000) were categorized into 50-mV increments (−151 to −200 mV, −201 to −250 mV, etc.).

This correlation showed that practically all of the concretes were in sound condition at potentials greater than or equal to −150 mV, and all the concretes were deteriorated at less than or equal to −450 mV (see Figure 1). However, this correlation was characterized by deviations of varied degrees between these extremes. For example, for concretes with potentials between −301 and −350 mV, only 28 to 85 percent were actually deteriorated; for concretes with potentials between −351 and −400 mV, only 70 to 100 percent were deteriorated. (It is believed that this correlation would still be generally valid even if a criterion other than 6 in. was used in classifying the condition of the concrete.) This observation agrees, in general, with the ASTM C-876 guidelines for interpretation of half-cell potentials, even though the guidelines attempted to relate potential only with probability for rebar corrosion.

It is clear that there was not a sufficiently well-defined relationship between concrete condition and the numerical values of individual half-cell potentials, with the exception of potentials at the extreme ends, that engineers can use to prepare repair plans with a reasonable degree of confidence. This also raises a concern about the appropriateness of replacing existing concrete simply because the potential is less than or

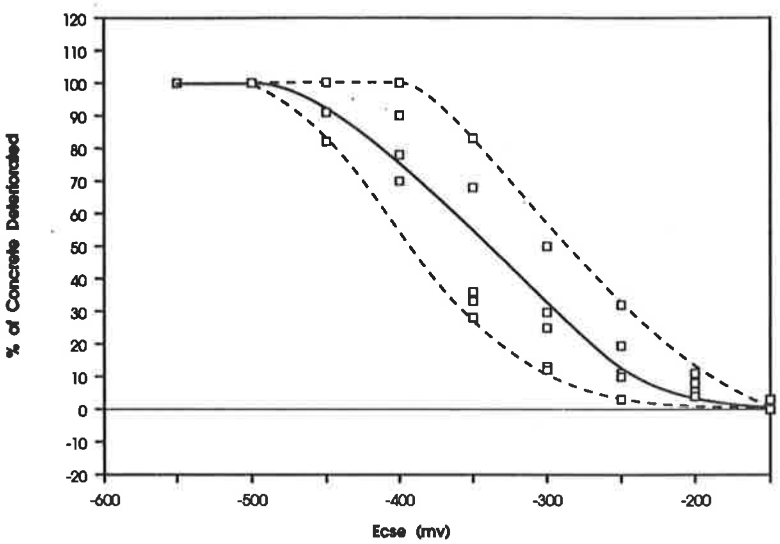

FIGURE 1 Correlation between half-cell potentials and frequency of damaged concrete observed in all survey areas.

equal to −350 mV, which is a common practice of many highway agencies.

As will be shown, the absence of such correlation is a result of fluctuation of half-cell potential at any location with time, which is likely in response to fluctuating temperature and moisture in the concrete.

Potential Gradients and Concrete Condition

It was found that a convenient and effective way to locate active rebar corrosion and its associated damage to the concrete is to plot the results of a half-cell potential survey on an iso-potential contour map, on which the variation in potential gradient is reflected by the spacing between the contour lines, such as that shown in Figure 2 for one of the areas surveyed.

Because of the nonhomogeneity of concrete and, therefore, the distribution of chloride ions across the concrete, the corrosion found on rebars and the associated damage to the surrounding concrete are often localized in nature. Consequently, as the reference electrode is moved from one location on the concrete where the rebar underneath is not corroding to another nearby location where the rebar is actively corroding, the half-cell potential should become more negative. Further, the probability that localized rebar corrosion is occurring at the second location increases as the potential shifts toward a more negative value at a relatively high potential gradient (i.e., the contour lines are closely spaced). Conversely, if the potential shifts toward a more positive value, the probability of localized rebar corrosion occurring at the next location decreases.

Accordingly, the existence of numerous areas where active rebar corrosion was likely to be occurring is indicated in Fig-

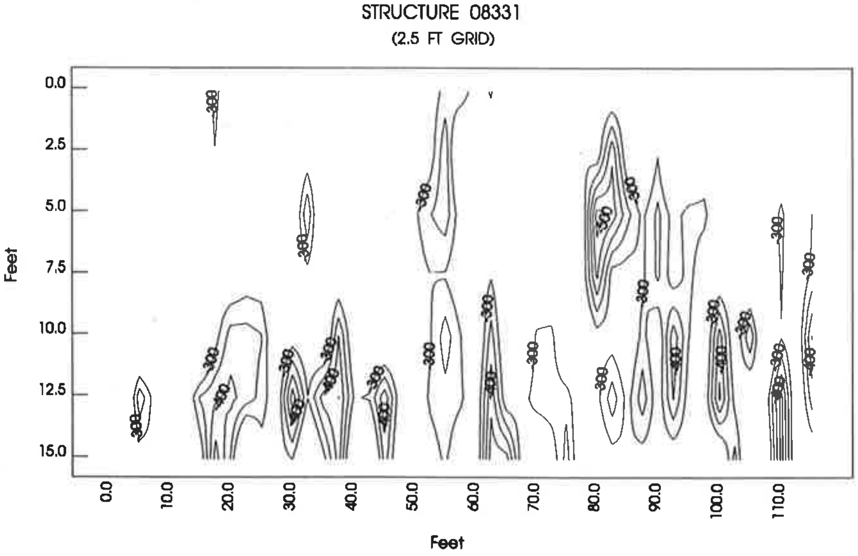

FIGURE 2 Iso-potential contour map for a survey area. (Only E ≤ −300 mV are plotted in 50-mV increments.)

ure 2. Over the surface of the concrete, the potential gradients corresponding to these areas ranged from approximately −72 to −172 mV/ft. It is worthwhile to note that the orientation of these areas coincided with the general alignment of the top transverse rebars of the deck, which are the rebars that are likely to corrode first.

Given sufficient time to corrode, the rebars would eventually accumulate a sufficient amount of oxidation products to initiate delamination in the surrounding concrete. Therefore, it is not unreasonable to expect that the concrete at some of the active areas indicated in Figure 2 would already be damaged, especially if the deck had been in service for 20 years. This was in fact the case. When the locations of all the transverse cracks and delaminations detected in the concrete were superimposed on the contour map in Figure 2 (as shown in Figure 3), it was evident that many of the deteriorated concrete areas matched the areas of high negative potential gradients.

A similar correlation between locations of high lateral potential gradients and locations of deteriorated concrete was found for the other survey areas involved in the study. In these areas, the potential gradients ranged from approximately −60 to −300 mV/ft.

It is estimated that at least 85 percent of the deteriorated concrete areas in the survey area depicted in Figure 3 were matched or accounted for by high potential gradients. The failure of this potential survey to account for or detect the remaining deteriorated concrete areas is attributed to the grid spacing of 2.5 ft used in the survey, which appeared to be too large. For example, consider the two narrow delaminated areas at around (61.0 ft, 2.5 ft) and (85.0 ft, 11.0 ft). The edges of both areas were located considerably far (at least 0.7 ft) from their nearest grid points for the effect of the localized corrosion on the rebars to be manifest on the potentials measured at those grid points.

Optimum Grid Spacing for Half-Cell Potential Surveys

To determine the optimum grid spacing, it was necessary to determine the maximum lateral distance from a corroding rebar at which the effect of corrosion on the half-cell potential was still discernible. Figure 4 shows a contour map that resulted from detailed measurements of half-cell potential, in an 0.5-ft spacing, around a typical small delaminated concrete area that was approximately 1.2 ft wide. The transverse rebar on which the corrosion that caused the delamination occurred was situated directly beneath the crack at the center; other transverse rebars were spaced 1 ft away. Again, the localized nature of rebar corrosion (and its resulting damage) was manifest in a large potential gradient, which was approximately −250 mV/ft in this case, as the potential shifted from −525 mV at the most active area (center top) to approximately −275 mV at 1 ft away on either side.

If the field of effect is defined as the maximum (lateral) distance from the edge of a delamination or crack to a point on the surface of the concrete where the half-cell potential has shifted sufficiently toward positive to indicate that the underlying rebar corrosion is almost indiscernible and if this potential is assumed to equal −300 mV, Figure 4 shows the field of effect to be less than 8 in. Therefore, if this delamination happened to fall in the middle of a 2.5-ft grid square, it would certainly not be detected. Because similar observations for the other decks indicated that the field of effect was typically no more than 8 to 10 in., it is quite clear that grid spacing of 2.5 ft—let alone the 4.0-ft spacing recommended by ASTM C-876 or the 5.0-ft spacing used by many highway agencies—would still be too large to provide a complete assessment of the condition of a concrete deck.

It appeared that the optimum grid spacing was approximately 1.0 ft. To ascertain this, a 1.0-ft grid spacing was used to conduct a half-cell potential survey on another concrete

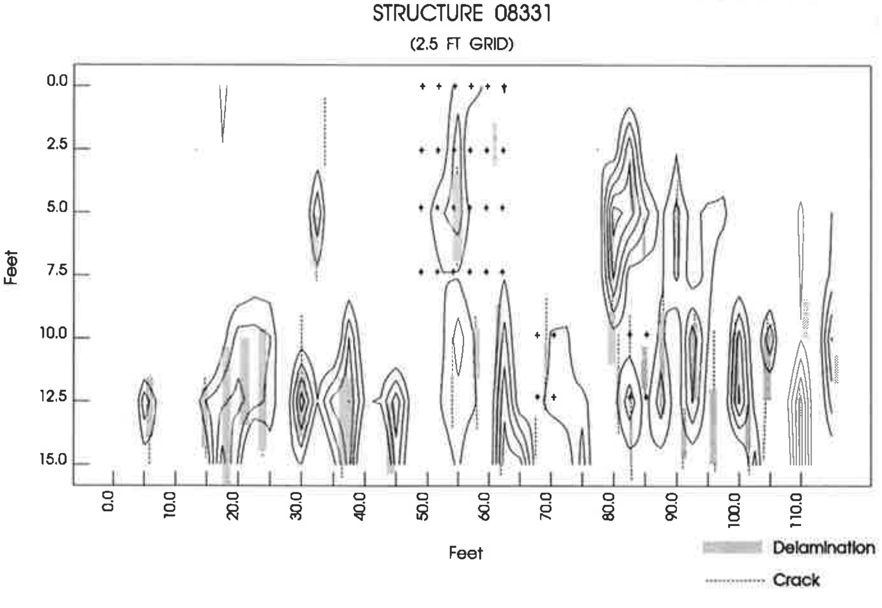

FIGURE 3 Correlation of transverse cracks and delaminations with potential gradients (2.5-ft grid spacing).

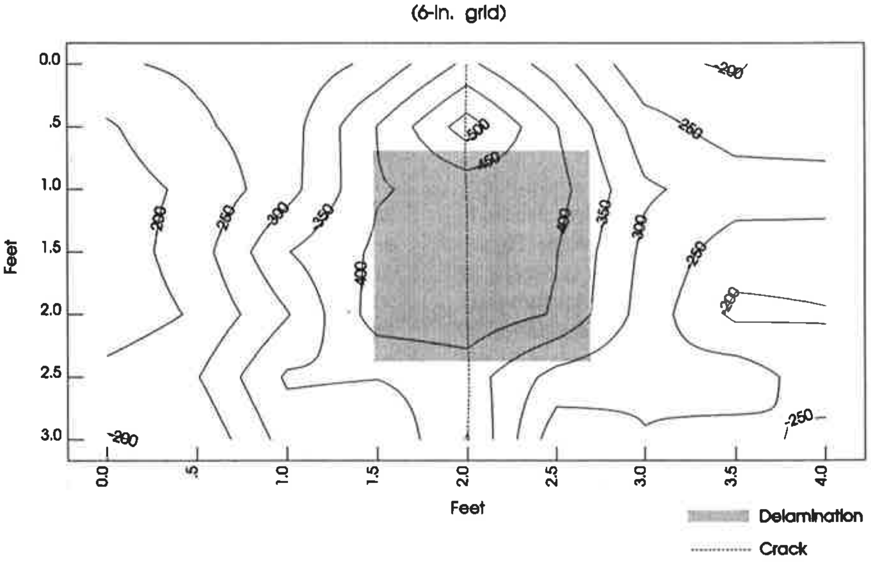

FIGURE 4 Iso-potential contour lines surrounding a deteriorated concrete area.

deck. Then, in addition to the usual analysis of the entire set of data, analyses to simulate the use of 2.0-ft and 4.0-ft spacings were also conducted by simply disregarding potentials measured at appropriate grid points during different simulations.

The iso-potential contour map that resulted from the use of 1.0-ft grid spacing (see Figure 5) clearly delineated the presence of numerous areas of high potential gradients, ranging from −100 to −300 mV/ft. These areas coincided with or accounted for all the delaminations and severe transverse cracks detected.

The contour map also showed several areas in which the potential gradients were high, indicating the presence of relatively active rebar corrosion, but the concrete was still reasonably sound (with the exception of the presence of some fine cracks) by the sounding inspection. In fact, the rebar corrosion rates in a few of these areas (A, B, and C) were measured by a 3LP device and found to be 2.87, 2.94, and 3.09 mA/ft^2, respectively; these rates were approximately 3 times higher than those found at grid points (13, 3) and (21, 1), which were 0.99 and 1.06 mA/ft^2, respectively.

Based on the generalized correlation between rebar corrosion rate and metal loss that was found to be true for several decks (with 19 to 23 years of service), the level of corrosion observed in areas A, B, and C may translate to a metal loss of approximately 2 percent to 6 percent by weight (see authors' other paper in this Record). Such metal loss is just below an estimated threshold at which concrete could begin to fracture, 3 to 6 percent by weight. This implies that if repair is contemplated a bridge engineer should include the small areas of A, B, C, and others in Figure 5 in the estimation of the quantity of necessary repair. This raises an issue that must be addressed in a future study—the determination of the extent of concrete in each area of high potential gradient that

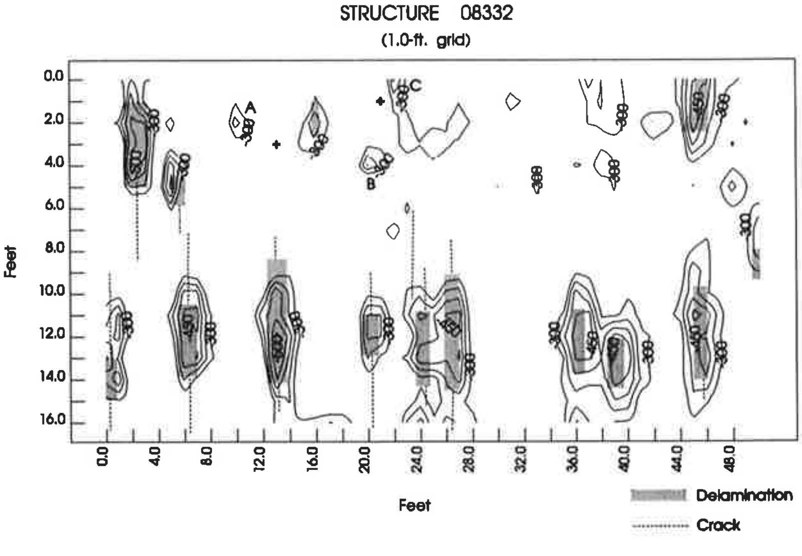

FIGURE 5 Iso-potential contour map obtained with 1.0-ft grid spacing.

must be included in the estimation of the quantity of necessary repair.

If a 2.0-ft grid spacing was used instead, as shown in Figure 6, the delamination at the vicinity of grid point (6, 5) became practically unaccounted for as a consequence of the incomplete data provided by this slightly larger grid spacing. Further, there were some losses of details and distortion of the configurations of some areas of high potential gradients. However, these errors were relatively small and probably negligible.

If an even larger, 4.0-ft grid spacing was used, the corresponding sampling of the same area would be so insufficient that approximately 50 percent of the deteriorated areas would be left undetected, and the areas of high potential gradients would be seriously distorted (Figure 7). The results would not represent the condition of the deck area surveyed with reasonable accuracy.

The failure rate in detecting areas of active rebar corrosion and concrete deterioration for a given grid spacing, with respect to the 1.0-ft grid spacing, was estimated based on two survey areas from which appropriate data were available (see Figure 8). Assuming that the failure rate for 1.0-ft grid spacing was 0 percent, the rate increased to 10 percent for 2.0-ft grid spacing and then abruptly to approximately 62 percent for 4.0-ft grid spacing. Although these failure rates may represent only the two particular survey areas, they nevertheless serve to illustrate that the reliability of a half-cell potential survey

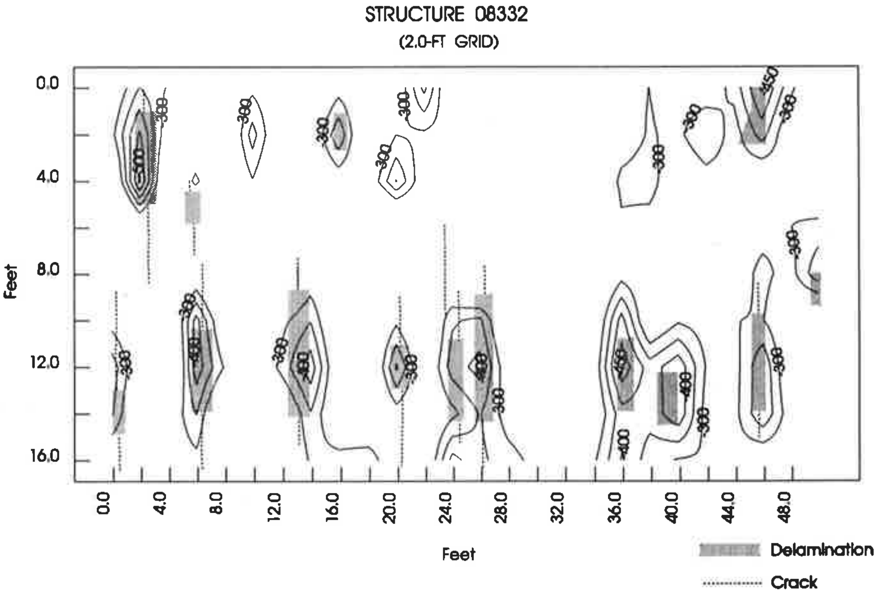

FIGURE 6 **Iso-potential contour map obtained with 2.0-ft grid spacing.**

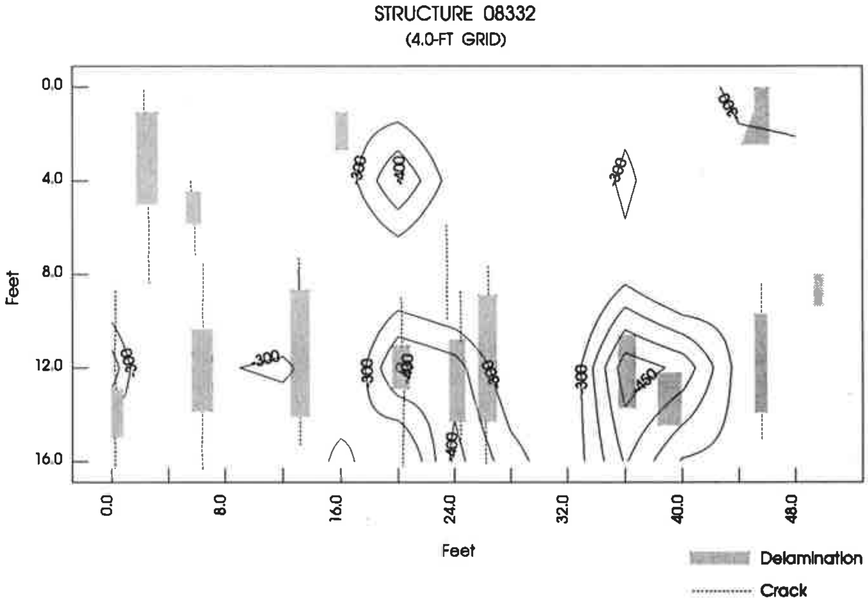

FIGURE 7 **Iso-potential contour map obtained with 4.0-ft grid spacing.**

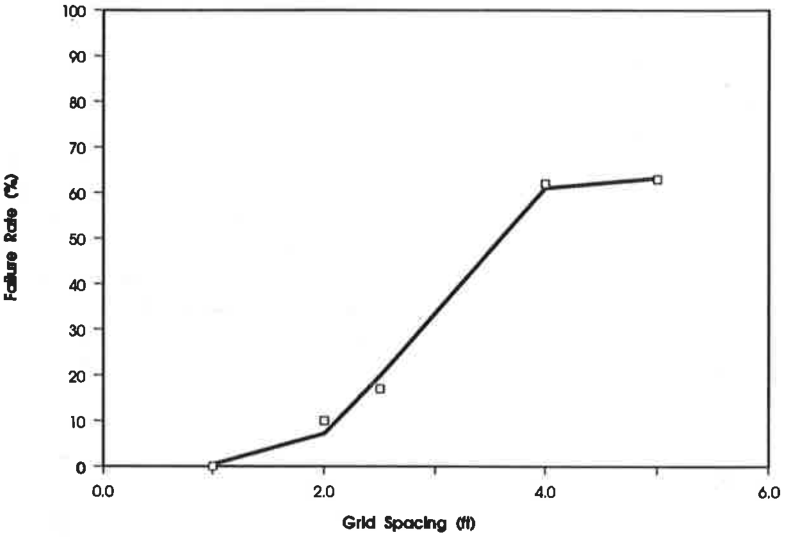

FIGURE 8 Effect of survey grid spacing used in half-cell potential surveys on the estimated failure rate for locating corrosion-induced deterioration in concrete bridge decks.

to provide a complete picture of the condition of a deck is considerably jeopardized when a large grid spacing, especially one larger than 2.0 ft, is used.

Of course, as the grid spacing is reduced, the required amount of sampling (or number of potential measurements) in a survey increases exponentially, as illustrated in Figure 9. If a 1.0-ft spacing were used, 1,084 individual potential readings would have to be recorded for 1,000 ft^2 of concrete deck area. The amount of sampling required decreases significantly by 73 percent or 87 percent when the spacing is increased to 2.0 or 3.0 ft, respectively. Beyond these grid spacings, the corresponding decrease in sample size required is comparatively less.

Selection of an optimum grid spacing should reflect a balance between reasonable accuracy (consistent with the purpose of the survey) and a reasonable sample size (with its associated survey time and cost). Consider the influence of a desired accuracy on the sample size required per unit percentage of accuracy, as shown in Figure 10. For the 100 percent accuracy provided by 1.0-ft spacing, the sample size required would be 10.8 measurements of potential per 1,000 ft^2 of concrete per percentage accuracy. In contrast, for the 90 percent accuracy provided by using a 2.0-ft grid spacing, the required sample size would be only 3.26 measurements per 1,000 ft^2 of concrete per percentage accuracy.

It must be emphasized that even though use of a small grid spacing would increase sample size exponentially, the concomitant survey and analysis time would increase only minimally by using an array of $Cu/CuSO_4$ electrodes and a portable microprocessor-based data recorder similar to those used in this study. However, if a compromise between accuracy and required sample size is necessary, the 2.0-ft spacing is

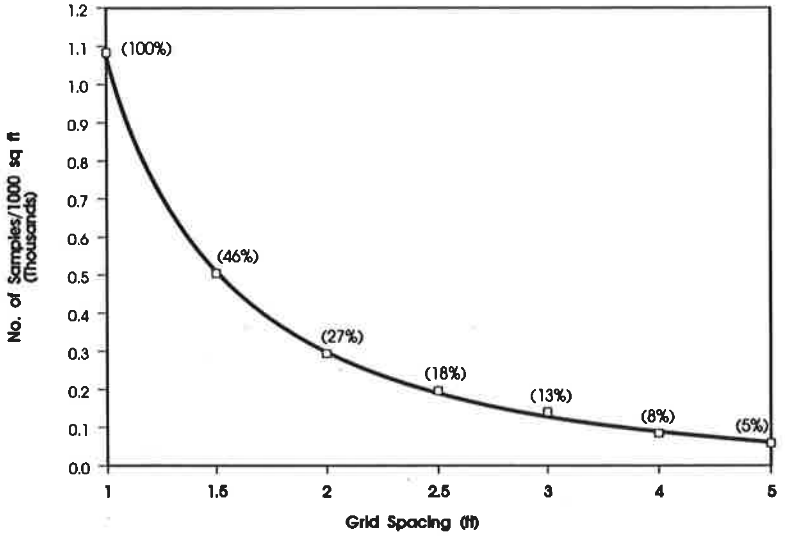

FIGURE 9 Number of sample locations in survey grid used for half-cell potential survey as a function of square grid spacing.

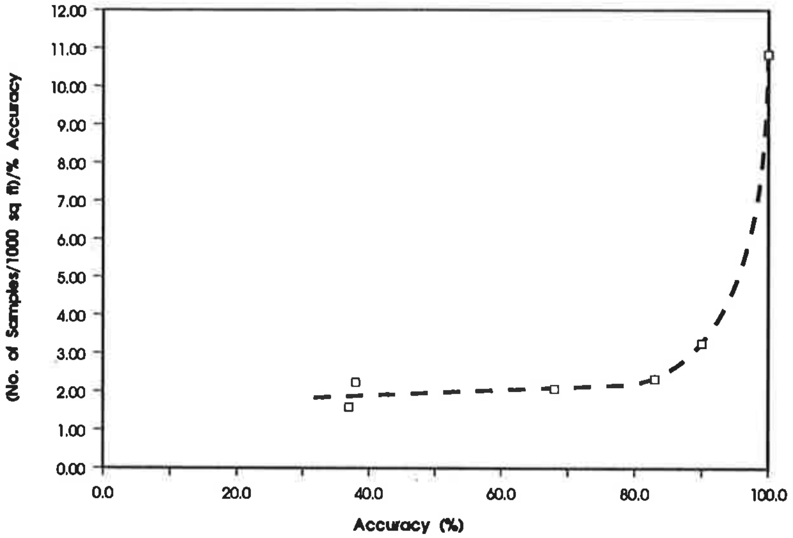

FIGURE 10 Influence of desired accuracy on number of half-cell potential measurements required per 1,000 ft^2 of concrete deck per percentage of accuracy.

undoubtedly a reasonable choice, especially considering that the field of effect on the potential from a corrosion site may be 8 to 10 in.

Influence of Concrete Variables on Half-Cell Potentials

Half-cell potentials reflect not only the condition of the rebars and the concrete, as discussed previously, but also the electrical resistance of the layer of concrete between the rebars being measured and the Cu/CuSO$_4$ electrode. Because the resistance of the concrete at any location in a deck is determined to various degrees by the thickness of the concrete layer and the seasonally fluctuating variables of temperature and moisture content, half-cell potentials can fluctuate from survey to survey. The researchers believed that such fluctuation has contributed to uncertainty concerning the interpretation of half-cell potentials.

Because of this fluctuation, it is important to consider the potentials measured in any survey not in terms of their magnitude or numerical value (as recommended by the interpretation guidelines in ASTM C-876) but in terms of their relation to the magnitude of the potentials measured at the surrounding concrete.

This point can be demonstrated easily by superimposing contour maps from separate surveys of the same concrete deck area. Figure 11 shows the contour map in Figure 6 super-

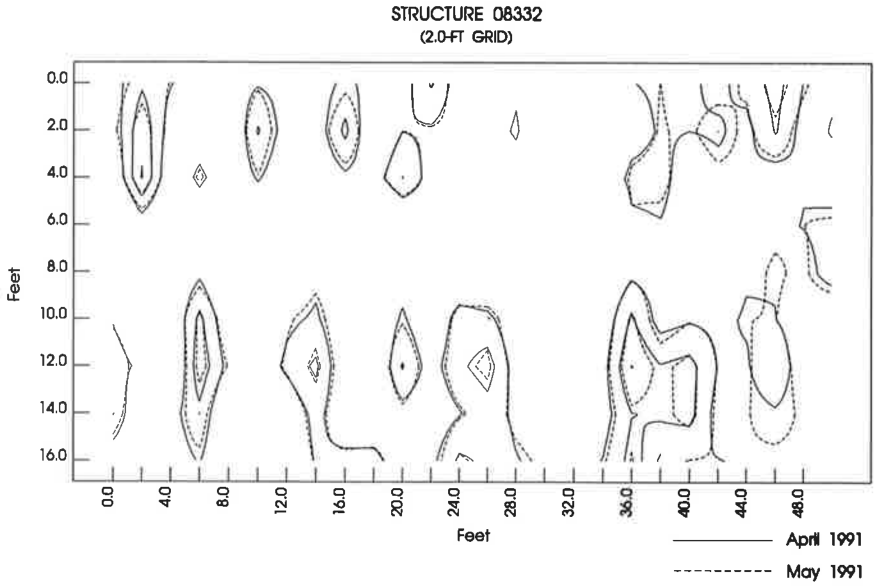

FIGURE 11 Contour maps of half-cell potentials observed during two separate surveys of a section of a concrete deck. (Iso-potential lines in 100-mV increments, starting at −300 mV.)

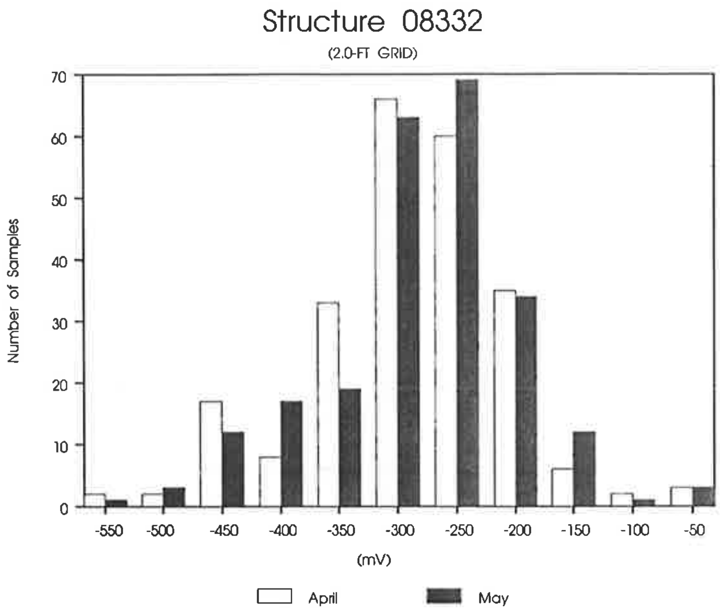

FIGURE 12 Frequency histograms of half-cell potentials observed during two separate surveys of a section of a concrete bridge deck.

imposed on another obtained a month earlier for the same concrete deck area. (The moisture content in the concrete deck may be relatively higher during the earlier survey because of rainfall in the area days before the survey.) With the exception of some minor differences, it is evident that the contour maps remained quite similar. More important, the general locations of the defective areas remained constant, despite some apparent differences in the histograms for the two sets of half-cell potentials (see Figure 12).

As the results show, as long as the overall condition of a concrete deck has not changed significantly between surveys, the resulting contour patterns should remain relatively unaltered, although the numerical values of the separate sets of half-cell potentials may vary. Therefore, the researchers argue that the numerical value of each measured potential by itself is a poor indicator of the condition of the rebars and the concrete; instead, a high potential gradient is a better indicator.

CONCLUSIONS

1. The half-cell potentials in a concrete deck can vary from one survey to another, likely due to the influence of fluctuating temperature, moisture, and oxygen in the concrete. Therefore, the numerical value of each measured potential by itself is a poor indicator of the condition of the rebars or the concrete.
2. The localized nature of rebar corrosion (and the associated damage to the rebars and the concrete) leads to the manifestation of corrosion in large potential gradients on the surface of the concrete deck. Such potential gradients may range from −60 to −300 mV/ft. Consequently, a high potential gradient would be a better indicator of the locations of actively corroding rebars and damaged concrete than the numerical values of individual potentials.
3. Even the 4.0-ft grid spacing recommended in ASTM C-876 for half-cell potential surveys was found to be too large to allow location of all existing areas of corroded rebars and damaged concrete in bridge decks. This is likely a result of the localized nature of rebar corrosion and the resulting damage. Although a spacing of 1.0 ft is preferable, a spacing of no more than 2.0 ft would provide a reasonable balance between accuracy and required sample size.
4. A half-cell potential survey can be used to locate and reasonably quantify areas of active rebar corrosion and corrosion-induced damage to the concrete in a concrete bridge deck when conducted using a grid spacing of no more than 2.0 ft and plotting the recorded half-cell potentials on contour maps.

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