INCORPORATING SET-UP INTO DRIVEN PILE DESIGN AND INSTALLATION

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After installation, pile capacity increases with time. This time-dependent capacity increase is known as set-up, and was first mentioned in the literature in 1900 by Wendel. Set-up has been documented in fine-grained soils in most parts of the world, and has been demonstrated to account for capacity increases of up to 12 times initial. The rate and magnitude of set-up is a function of a number of factors, the interrelationship of which is not well understood.

Set-up is predominately associated with an increase in shaft resistance, and is related primarily to dissipation of excess porewater pressures within, and subsequent remolding and reconsolidation of, soil which is displaced and disturbed as the pile is driven. Independent of changes in porewater pressure (i.e., independent of effective stress), additional set-up occurs due to aging.

Set-up is recognized as occurring in most parts of the world, for virtually all types of driven piles, in organic silt, inorganic saturated clay, and loose to medium dense silt, sandy silt, silty sand, and fine sand. Since set-up is related to dissipation of excess porewater pressures, the more-permeable the soil, the faster set-up develops. Set-up rate decreases as pile size increases.

A number of empirical relationships have been proposed to estimate or predict set-up, and have demonstrated reasonable success (accuracy) in a number of studies. Established relationships are limited in widespread application by having been based on combined (shaft and toe) resistance determinations, inter-dependence of back-calculated or assumed variables, and the complexity of the mechanisms contributing to set-up.

If justified by the scope (size) of a project, a well-designed and executed project-specific test program can yield more-valuable characterization of set-up than empirical relationships. Measurement of set-up requires that a pile's capacity be determined a minimum of 2 times. To maximize measured set-up, the first determination of a pile's capacity should be performed at the end of driving, or as soon after driving as possible, and the second determination should be delayed as long as possible (i.e., as long as the project schedule permits). Capacity determinations should separate shaft and toe resistance, and are most-valuable if the unit shaft resistance distribution (unit shaft resistance as a function of depth) is determined. Such capacity determinations can be achieved with top- or bottom-loaded internally instrumented static load tests, or dynamic testing with subsequent CAPWAP analyses, or preferably both.

Test programs which characterize only set-up magnitude, but not set-up distribution (i.e., where along the shaft set-up is occurring), lack flexibility in developing or modifying production pile installation criteria. Determination of not only set-up magnitude, but also set-up distribution (as a function of depth) provides such flexibility. Determination of set-up distribution also provides other design- and construction-phase flexibilities such as development of installation criteria which incorporate set-up for numerous different required production-pile capacities, and more-

Test Pile No.	Driving Status	Time After Initial Drive, in days	Penetration Depth, in feet	Toe Elevation, in feet	Penetration Resistance, blows/inches	Equivalent Penetration Resistance, blows/foot	Mobilized Capacity, kips			Capacity Fully Mobilized?
							Shaft	Toe	Total	
TP-15	EOID	-----	136.4	-127.6	19 / 1	228	58	380	438	No
	BOR	69	136.4	-127.6	6 / 0.5	144	322	378	700	No
TP-16	EOID	-----	135.1	-126.3	18 / 1	216	57	365	422	No
	BOR	69	135.1	-126.3	8 / 0.5	192	407	355	762	No
TP-17	EOID	-----	130.0	-121.2	7 / 1	84	90	331	421	Yes
	SLT	64	130.0	-121.2	-----	-----	724	220	944	Yes
	BOR	69	130.0	-121.2	9 / 0.5	216	371	455	826	No
TP-18	EOID	-----	131.0	-122.2	80 / 12	80	62	290	352	Yes
	BOR	69	131.0	-122.2	5 / 0.5	120	357	320	677	No
TP-19	EOID	-----	115.3	-106.5	11 / 4	33	130	69	199	Yes
	BOR1	0.7	115.3	-106.5	11 / 1	132	178	290	468	No
	BOR2	70	115.7	-106.9	10 / 0.5	240	463	310	773	No

Table 1. Pile test program data summary.

accurate assignment of reduced capacities to short or damaged piles.

To aid in determining the magnitude and distribution of set-up, static load test piles can be internally instrumented to determine shaft resistance distribution, and test piles can receive restrike testing (i.e., can be restruck). The piles' potentially increased impedance (e.g., from concrete fill) notwithstanding, because of set-up, a larger hammer with greater impact force than used for initial driving may be required to mobilize the piles' capacities (move the piles) during restrike testing.

A pile test program case history is presented herein which demonstrates the characterization of unit set-up distribution (unit set-up as a function of depth), and the development of depth-variable penetration resistance criteria, for high-capacity (190-ton allowable load) pipe piles in Milwaukee, Wisconsin.

PROJECT DESCRIPTION

The Sixth Street Viaduct Replacement Project involved demolition of the existing Sixth Street Viaduct, and construction of its replacement. The 4 major project structures were two bascule bridges, and two cable-stayed bridges. Because of the magnitude of load at each structure, and the number of piles required, a pile test program was performed at each of the 2 bascule bridges, and at each of the 2 cable-stayed pylon structures. The pile test program presented herein was performed at the south pylon structure. The south pylon structure consists of 2 single towers, each 136 feet high. At each tower, design compression load is approximately 7,000 kips, with transverse and longitudinal moments approaching 20,000 foot-kips.

SUBSURFACE CONDITIONS

Subsurface explorations and geotechnical evaluations were performed for the project by others. Boring depths ranged from 121 to 224 feet. Subsurface conditions consisted of fill deposits comprised of silty clay, to fine to coarse sand, extending to a depth of approximately 4 feet, underlain by native loose to medium dense fine-grained granular deposits consisting of clayey silt, to fine sand, which extended as deep as 29 feet. Underlying deposits consisted predominately of very stiff silty clay, with occasional layers of loose to medium dense clayey or sandy silt, to the termination depths of the borings.

PILE TEST PROGRAM

Installation

General

The test piles consisted of steel pipe piles having an outside diameter of 12.75 inches and a wall thickness of 0.375 inch. A total of 5 indicator piles were installed. The test piles were installed closed-end, using a Delmag D30-32 single-acting diesel hammer.

Dynamic Monitoring

Initial driving of the test piles was dynamically monitored using a Pile Driving Analyzer® ("PDA") instrumentation system. Additional analysis of field-measured dynamic monitoring data included performing a CAse Pile Wave Analysis Program® ("CAPWAP") analysis on a representative blow from the end of initial drive ("EOID") of each indicator pile. All EOID CAPWAP analyses were performed using the residual stress analysis ("RSA") option. The PDA data and subsequent CAPWAP analyses were used to determine pile capacities, the division of capacity between toe and shaft resistance, and shaft resistance distribution.

Restrike Testing

General

Determination of unit set-up is typically appropriate for discrete pile sections, such as some fraction of the total pile length for CAPWAP analyses. Unit set-up for a particular pile segment is defined as the shaft resistance increase attributable to set-up for that pile segment, divided by the surface area of that pile segment.

Restrike testing was performed 69 to 70 days after EOID using a Delmag D36-32 single-acting diesel hammer.

Dynamic Monitoring

Restrike testing of the indicator piles was monitored using a PDA. Additional laboratory analysis of

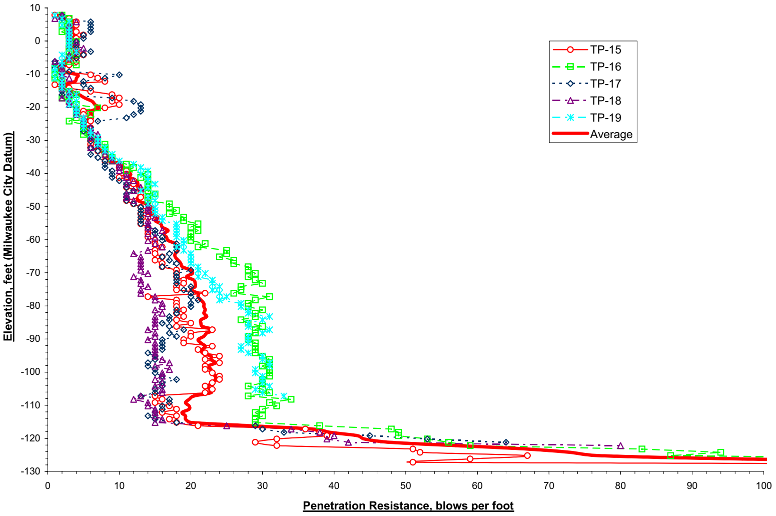

Figure 1. Penetration resistance vs. elevation.

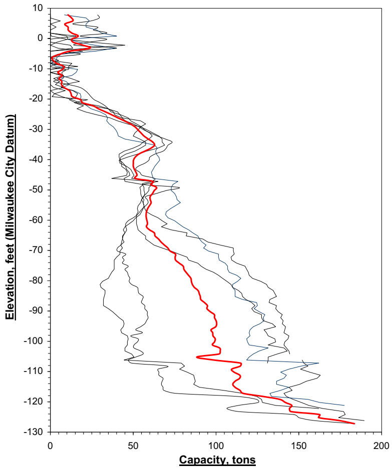

Figure 2. Initial-drive CASE-method capacity vs. elevation

field-measured dynamic monitoring data included performing a CAPWAP analysis on a representative blow from beginning-of-restrike ("BOR") testing for each pile. Similar to EOID CAPWAPs, all BOR CAPWAPs were performed using the residual stress analysis option.

RESULTS AND ANALYSIS

Select pile test program results are summarized in **Table 1**.

Installation

The driving behavior of the test piles is presented as a plot of penetration resistance versus elevation in **Figure 1**. Since the test piles were installed using a variable-stroke hammer, and since the penetration resistances presented in **Figure 1** do not account for variations in stroke, the penetration resistances are not directly comparable to each other. A more-direct comparison of driving behavior can be made using Case-method initial-drive capacities estimated by the PDA based on dynamic monitoring results. These data are presented as a plot of initial-drive Case-method capacities versus elevation in **Figure 2**.

CAPWAP analyses calculated the indicator piles' EOID unit shaft resistance distributions. The CAPWAP-determined EOID unit shaft resistance distributions are presented as plots of unit shaft resistance versus elevation in **Figure 3**.

Restrike Testing

CAPWAP analyses calculated the indicator piles' BOR unit shaft resistance distributions. The CAPWAP-determined BOR unit shaft resistance distributions are presented as plots of unit shaft resistance versus elevation in **Figure 4**.

Set-Up

CAPWAP-determined unit set-up distributions were calculated for each indicator pile by subtracting the EOID CAPWAP-determined unit shaft resistance distribution from the BOR CAPWAP-determined shaft resistance distribution (i.e., by subtracting the values presented in **Figure 3** from those presented in **Figure 4**). The accuracy of the resulting difference (the unit set-up distribution) is sensitive to the accuracy (i.e., the degree to which capacity was mobilized) of both the EOID and BOR unit shaft resistance distribution. An assessment of whether each indicator piles' EOID or BOR capacity was fully mobilized is included in **Table 1**.

If both EOID and BOR capacity are fully mobilized, set-up is determined to a reasonable degree of accuracy. If EOID capacity is fully mobilized but BOR capacity is not fully mobilized, set-up is underestimated. If EOID capacity is not fully mobilized but BOR capacity is fully mobilized, set-up is overestimated. If neither EOID nor BOR capacity is fully mobilized, the effect on the accuracy of set-up determination is uncertain. These scenarios are illustrated in **Table 2**, along with each of the test piles' situation among these scenarios.

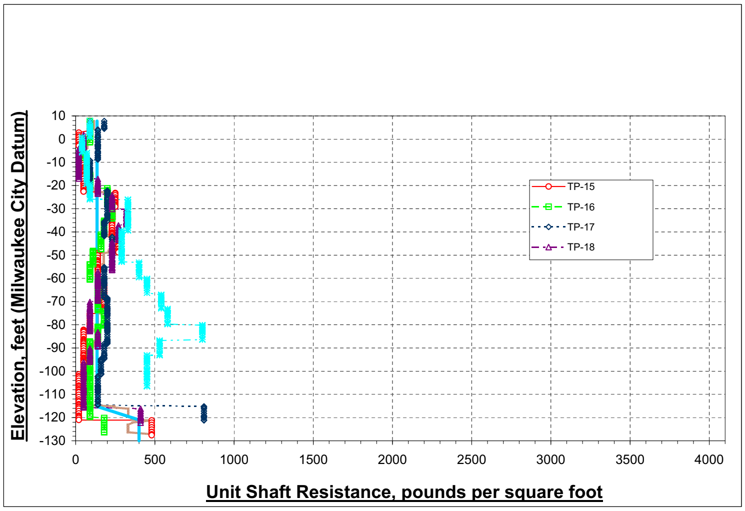

Figure 3. EOID CAPWAP unit shaft resistance vs. elevation.

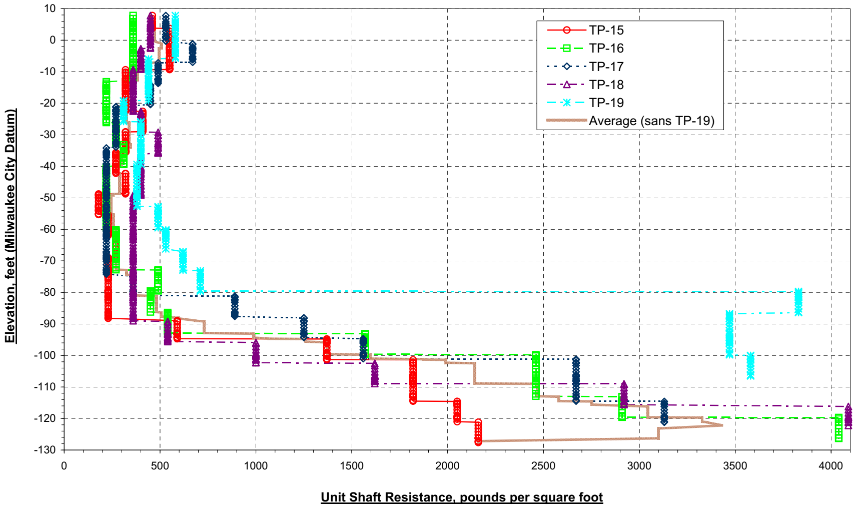

Figure 4. BOR CAPWAP unit shaft resistance vw. elevation.

		BOR Capacity	
		Fully Mobilized	Not Fully Mobilized
EOID Capacity	Fully Mobilized	Set-up Reasonably ccurate TP-18?	Set-Up Underpredicted TP-17 TP-18? TP-19
	Not Fully Mobilized	Set-up Overpredicted	Set-Up Indeterminate TP-15 TP-16

Table 2. Relationships between EOID and BOR capacity mobilization and determination of set-up.

The CAPWAP-determined unit set-up distributions are presented as plots of unit set-up versus elevation in Figure 5. The test piles' unit set-up distributions being either reasonably accurate, underpredicted, or indeterminate notwithstanding, a review of **Figure 5** indicates that, with the exception of TP19, the CAPWAP-determined unit set-up distributions show relatively good correlation with each other. A review of **Figure 5** indicates that the indeterminate unit set-up distributions (TP15 and TP16) were similar to, or less than, those which were reasonably accurate, and to those which were underpredicted.

Application to Design and Installation

Unit Set-Up Distribution Used for Design

The unit set-up distribution used for design is presented in **Figure 5**. Its application to design is discussed in the following sections.

Allowable Loads Available for Production Piles

For a given toe elevation, the capacity to which piles can be installed is the sum of 2 components: the initial-drive capacity (e.g., as presented in **Figure 2**), plus set-up. It follows that to aid in estimating capacities to which production piles could be installed, the initial-drive capacity and set-up can be added. The result of such an evaluation for piles of the same type as the test piles, and installed using the same hammer as the test piles, is presented in Figure 6. The cumulative set-up curve in Figure 6 was obtained by applying the unit set-up distribution used for design presented in Figure 5 to the surface area of a 12.75-inch-O.D pipe pile. A review of Figure 6 indicates that piles terminating at approximate Elevations 117 and 123 would attain 50 percent of their long-term capacity from set-up.

A review of **Figure 6** indicates that within the depths explored by the test piles, dynamic monitoring results indicated that 12.75-inch-O.D production piles installed using a hammer with a transferred energy similar to that used for the test program (a Delmag D30-32) could achieve capacities of about 345 tons (of which 160 tons, or 46 percent, is set-up), resulting in potential allowable capacities on the order of 172 tons. A review of Table 1 indicates that full capacity was not mobilized for any of the test piles during restrike testing. As presented in **Table 2**, the test piles' unit set-up distributions were either reasonably accurate, underestimated, or indeterminate. A review of **Figure 5** indicates that the indeterminate unit set-up distributions (TP15 and TP16) were similar to, or less than, those which were reasonably accurate, and those which were underpredicted. Accordingly, the values of capacity, set-up magnitude and percentage, and potential allowable load presented in **Figure 6** are likely conservative (lower than actual).

For the south pylon structure, it was desired to install the production piles to as high a capacity as practical. Using GRLWEAP, the drivability of higher-capacity production piles of the same pile section as the test piles, but using the Delmag D36-32 hammer (which was used for restrike testing), was evaluated. It was determined that the larger hammer would provide enough additional capacity at EOID without damage to the piles that, when combined with set-up, a capacity of 380 tons was achievable, resulting in a production-pile allowable load of 190 tons.

Pile : 12.75x0.37 5 Hammer : D36-32 Allowable Load: 190 tons

Pile Toe Depth, feet		Required Penetration Resistance, blows per foot									Pile Toe Elevatio n	
		Hammer Stroke, feet										
from	to	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	from	to
115	117								-----	----	-112	-114
118	120					-----	-----	-----	219	137	-115	-117
121	123			-----	-----	229	139	102	80	65	-118	-120
124	126	-----	-----	136	97	76	61	51	44	39	-121	-123
127	129	110	75	58	48	41	36	32	29	26	-124	-126
130	132	49	40	34	30	27	25	22	21	19	-127	-129
133	135	30	26	23	21	19	18	17	16	15	-130	-132
136	138	20	18	17	15	14	14	13	12	12	-133	-135
139	141	15	14	13	12	11	11	10	10	10	-136	-138
142	144	12	11	10	10	9	9	9	8	8	-139	-141
145	147	9	9	9	8	8	8	8	7	7	-142	-144

Table 3. Minimum required production-pile penetration resistance criteria.

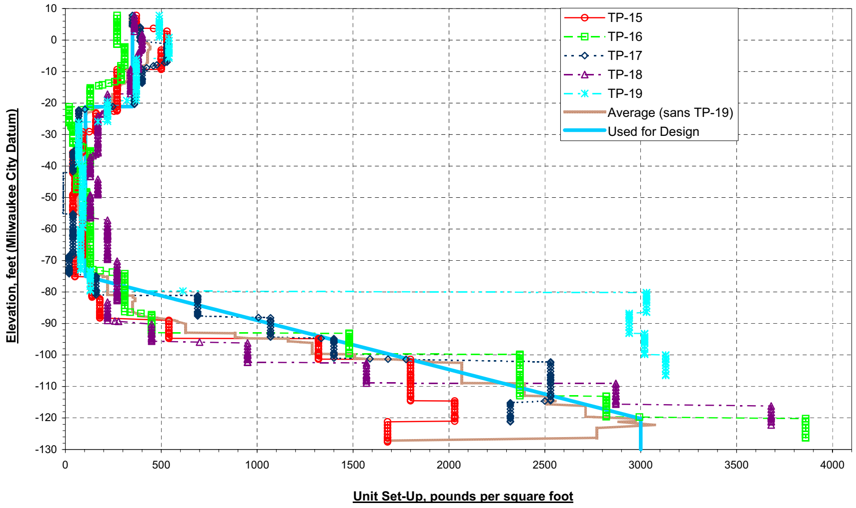

Figure 5. EOID/BOR CAPWAPs unit set-up vw. elevation.

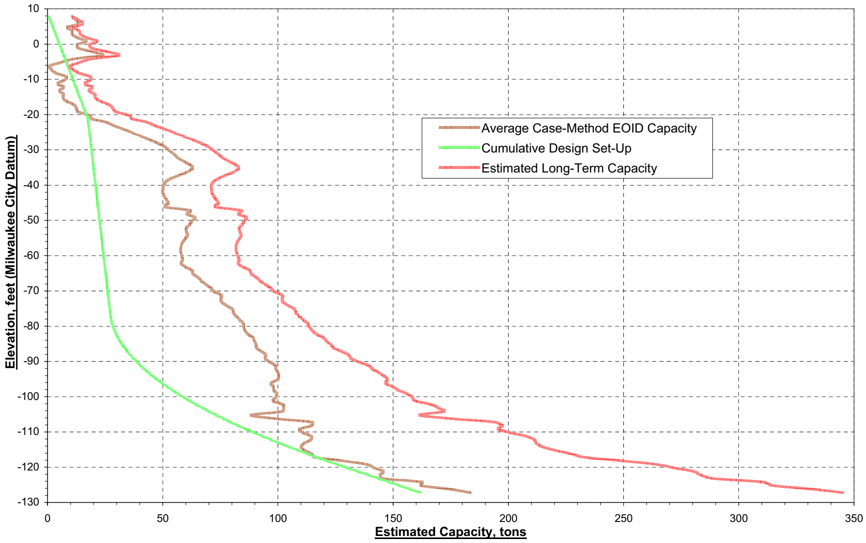

Figure 6. Estimated ultimate capacity vs. elevation - Delmag D30-32 - 12.75-inch pipe pile.

Penetration Resistance Criteria

Subsequent to EOID, a pile's capacity increase attributable to set-up is a function of the embedded side area of the pile, and the unit set-up distribution. The greater a pile's embedment length, the more set-up it develops, and the less EOID capacity is required. In this way, as required EOID capacity decreases with increasing embedment depth, so does required penetration resistance. Therefore, the cumulative set-up distribution for 12.75-inch-O.D. pipe piles presented in **Figure 6** was used to develop depth-variable production-pile penetration resistance criteria which decreased with increasing embedment depth. These criteria are presented in **Table 3**.

Depth-variable penetration resistance criteria account for both the variability of the driving behavior of individual piles (EOID capacity as evidenced by penetration resistance which may vary with depth and location), and the variability of set-up with depth (set-up distribution). This approach allows flexibility in addressing such design- and construction-phase issues as developing depth-variable installation criteria for numerous different required production-pile capacities, and more-accurate assignment of reduced capacities to short or damaged piles.

Production-Pile Installations

The 190-ton (allowable load) production piles driven for the 2 towers at the south pylon structure had an average embedded depth of 123 feet, corresponding to an average toe elevation of 119. Ignoring pile-cap costs, the 190-ton production piles driven for the 2 towers at the south pylon structure had an average support cost of $13.92 per allowable ton supported (support cost is the cost of the installed or constructed foundation element divided by its allowable load). At this location, the relatively deep embedment depths required to reach strata which provided high EOID capacities tended to increase support costs, while the contribution to required capacities from set-up tended to decrease support costs.

CONCLUSIONS

- Set-up can account for a significant portion of long-term pile capacity. For the case history presented, up to 50 percent of long-term capacity can be attributed to set-up.

- Accounting for set-up in pile design offers a number of benefits, and can result in the use of smaller hammers, smaller pile sections, shorter piles, higher capacities, and more-economical installations (lower support costs) than otherwise possible.

- The characterization not only of set-up magnitude, but also of set-up distribution, offers design- and construction-phase advantages, such as developing depth-variable installation criteria which incorporate set-up for numerous different required production-pile capacities, and more-accurate assignment of reduced capacities to short or damaged piles.

- Dynamic monitoring at both EOID and BOR, in conjunction with subsequent CAPWAP analyses, provides a means to determine both set-up magnitude and distribution.

- Subtraction of the CAPWAP-determined EOID shaft resistance distribution from the CAPWAP-determined BOR shaft resistance distribution provides a means to determine set-up distribution.

- Whether or not full capacity is mobilized during EOID and/or BOR dynamic testing, and the associated effects on calculated set-up distributions, should be recognized and accounted for in selecting a design set-up distribution, and in selecting potential allowable production-pile loads.

- Since set-up is predominately a shaft-resistance phenomenon, and since residual stress and non-residual stress CAPWAP analyses can result in different shaft resistance predictions, the type of analyses (i.e., residual versus non-residual) used to determine set-up distribution should be the same for both EOID and BOR data.

- Piles exhibiting differing driving behavior can exhibit similar set-up distributions.

- Initial-drive dynamic monitoring results, in conjunction with set-up distributions, can be used to predict piles' long-term capacities as a function of depth. This information can prove useful when evaluating potential production-pile sections and allowable capacities.

ACKNOWLEDGEMENTS

The introductory discussion of set-up presented herein is based partly on research funded by the Wisconsin Department of Transportation and the United States Department of Transportation in the interest of information exchange, and is the result of research done under the auspices of the Department and the Wisconsin Highway Research Program.

This article is based on a paper presented at PDCA's September 2002 Symposium. The original paper may be obtained by contacting the author at komurka@wkg2.com.