New Bedding Factors for Vitrified Clay Sewer Pipes

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The present bedding factors used by the clay pipe industry are dependent only on the bedding type. This practice has led to extremely conservative designs of these buried pipes and to their perceived inability to support deep covers of soil. Due to this conservative approach, clay pipe installations under deep fills were considered to be impossible and other materials have been used instead despite the many advantages clay pipe has offered for these projects. In this study, new bedding factors were predicted by the finite element analyses of buried vitrified clay pipes with four types of backfill and bedding materials. These bedding factors were calculated as the ratio of the maximum tensile strain in the computer-simulated three-edge bearing test of vitrified clay pipes to that in the finite element analyses of buried pipes. The new bedding factors are generally higher than those given in the current ASTM specifications. It is shown that the bedding factors are affected by the backfill material type and compaction density, backfill height, trench width, and pipe diameter. Design practice around the world is also summarized in this paper.

The design of buried vitrified clay pipes involves determining the maximum loads to which the vitrified clay pipes will be subjected in service and ensuring that the installed vitrified clay pipes under a certain bedding condition will provide field-supporting strength great enough to withstand the loads with a reasonable degree of safety. For vitrified clay pipes transporting sewage and other industrial effluents, the backfill loads, which were discussed in another paper (*1*) by the same authors, are usually the most important loads to be considered. The purpose of this paper is to study the field-supporting strength of buried vitrified clay pipes.

The field-supporting strength of vitrified clay pipes is influenced by many factors, such as physical properties of the vitrified clay pipes, bedding materials, depth of soil cover, trench width, degree of compaction of the trench materials, and workmanship. The physical properties of vitrified clay pipe determine its inherent strength (*2*). The bedding factor is the ratio of the field-supporting strength to the three-edge bearing test strength of the vitrified clay pipe. The three-edge strength of the pipe is measured in the test laboratory at the manufacturing plant using a statistically significant sampling technique.

Vitrified clay pipes are installed under various bedding conditions. Different bedding conditions provide varying levels of support around vitrified clay pipes and, hence, give different bedding factors. Currently used bedding conditions and their corresponding bedding factors in the United States are given in ASTM Standards (*3*), as shown in Figure 1. These bedding factors, except that for crushed stone encasement, are based on the research conducted in the early part of this century by Spangler (*4*) and Schlick (*5*). Since then, there have not been any changes in these bedding factors in the United States.

In addition, the loads used on these clay pipes in the United States are still based on the worst possible predictions by the old Marston theory. The authors calculated much lower loads in comparison to Marston loads and these results were reported recently in another paper (*1*), in which details of the finite element model used, distributions of soil pressures around the pipe for various bedding conditions, and locations of critical stresses and strains in the clay pipe wall were provided. Thus, in U.S. design practice, conservative bedding factors and Marston loads resulted in conservative designs of clay pipe installations. During these 50 years of conservative design practice, several advances have taken place in the field of soil-pipe interaction. Large-scale laboratory research on the bedding factors of vitrified clay pipes has been conducted by Bland et al. (*6*) and Sikora (*7*). The soil-pipe interaction problems have been successfully analyzed using the finite element method by Duncan et al. (*8-11*), Jeyapalan et al. (*12-17*), Katona (*18*), Krizek et al. (*19*), and Leonards (*20*). Thus, the finite element method can provide an accurate method of evaluating bedding factors for vitrified clay pipes under various bedding conditions.

The purpose of this paper is to present the bedding factors of buried vitrified clay pipes under different bedding conditions as computed by finite element analyses.

MATERIAL PROPERTIES

The properties of three different sizes of vitrified clay pipes used in the analyses are presented in Table 1 based on published data (*20*). The Young's modulus for vitrified clay pipe listed in Table 1 is based on the test results reported by Sikora (*7*).

Four types of backfill and bedding conditions were used in the analyses; two degrees of compaction level were chosen for each type, as follows:

1. Well-graded gravel compacted to 85 and 95 percent of standard AASHTO dry density (GW85 and GW95).
2. Silty sand at 80 and 95 percent (SM80 and SM95).

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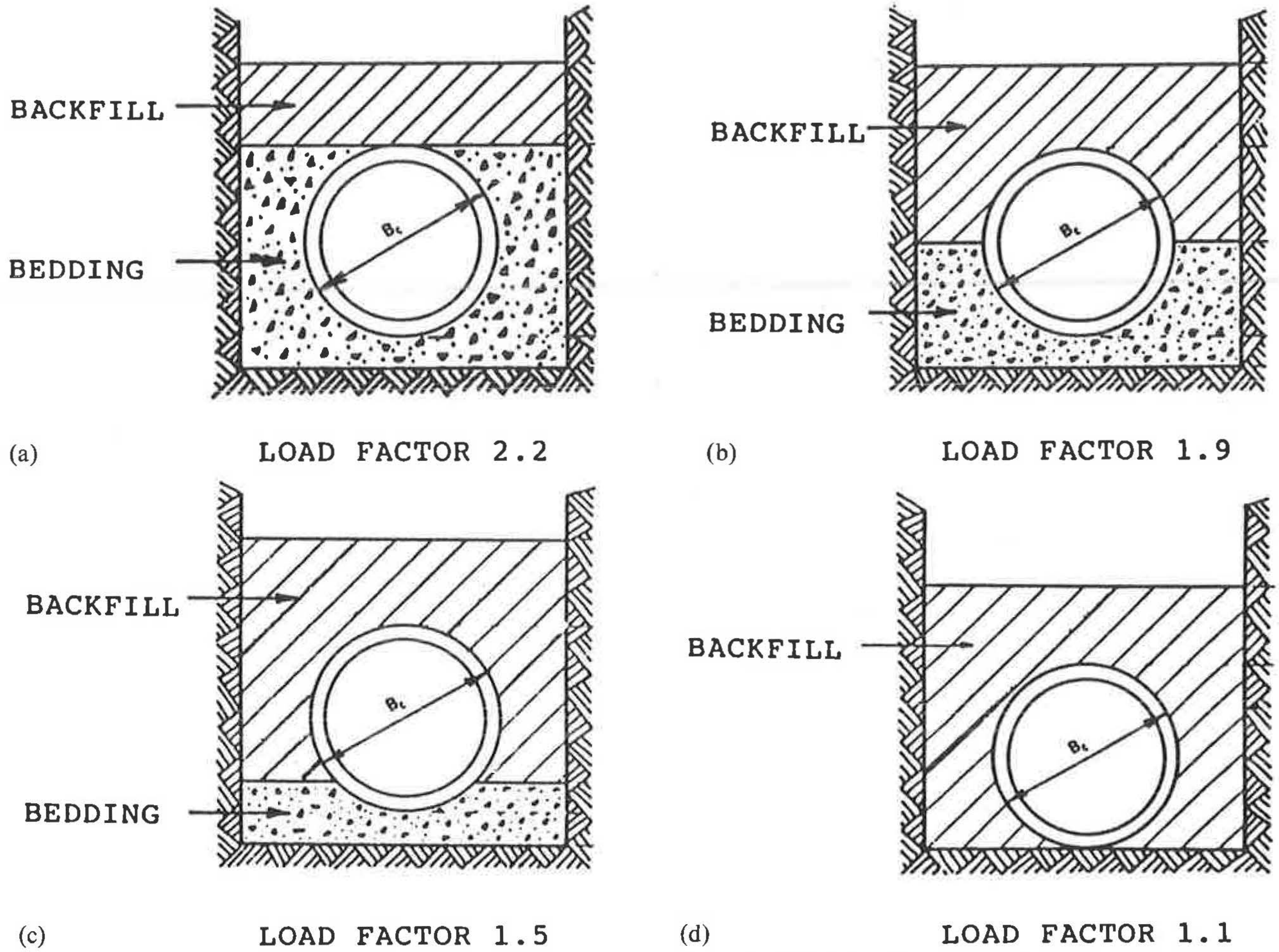


FIGURE 1 Current bedding conditions and their bedding factors for buried vitrified clay pipes: (a) Crushed stone encasement, (b) Class B, (c) Class C, and (d) Class D.

TABLE 1 PROPERTIES OF VITRIFIED CLAY PIPES USED IN ANALYSES

Pipes	Inner Diameter (in.)	Outer Diameter (in.)	Thickness (in.)	Area (ft^2/ft)	Moment of Inertia (ft^4/ft)	Young's Modulus (ksf)
6-in.	6	7.375	0.6875	0.05729	0.00001567	835,200
21-in.	21	25.5	2.25	0.1875	0.0005493	835,200
42-in.	42	51	4.5	0.3750	0.004395	835,200

3. Sand-clay-silt mixture at 80 and 95 percent (SM-SC80 and SM-SC95).
4. Low-plastic clay at 80 and 95 percent (CL80 and CL95).

Native soil used in all the analyses is low-plastic clay at 90 percent (CL90). The hyperbolic soil model parameters of soils used in the analyses are presented in Table 2.

FINITE ELEMENT ANALYSES

The interaction between the vitrified clay pipe and the surrounding soils was studied using the finite element method. The computer program used in the analyses is a plane-strain soil-pipe interaction finite element program. The hyperbolic stress-strain relationship of soils developed by Duncan et al. (*11*) was used in the program to approximate the nonlinear and stress-dependent stress-strain properties of the soils. The actual sequence of construction operation was simulated by a number of construction layers. The geometry of the trench was simulated in the analyses by using a finite width for the soil elements placed in each compaction lift. The load from the construction lift was applied in the analyses by converting the soil weight to equivalent nodal point forces.

A typical finite element mesh used in the analyses is shown in Figure 2. This mesh was used to model a 42-in. vitrified clay pipe with a backfill height of 50 ft and a trench width of 8 ft.

TABLE 2 SOIL PROPERTIES

Unified Classification	RC Standard AASHTO	γ kcf	C ksf	ϕ degrees	$\Delta\phi$ degrees	K	n	R_f	K_b	m	K_o
CW	85	0.130	0	30	2	100	0.4	0.7	25	0.2	0.5
	95	0.140	0	36	5	300	0.4	0.7	75	0.2	0.5
SM	80	0.115	0	28	1	75	0.25	0.7	50	0	0.5
	95	0.130	0	34	6	450	0.25	0.7	350	0	0.5
SM-SC	80	0.115	0.1	33	0	50	0.6	0.7	25	0.5	0.5
	95	0.130	0.4	33	0	200	0.6	0.7	100	0.5	0.5
CL	80	0.115	0.05	30	0	30	0.45	0.7	20	0.2	0.5
	95	0.130	0.3	30	0	120	0.45	0.7	110	0.2	0.5

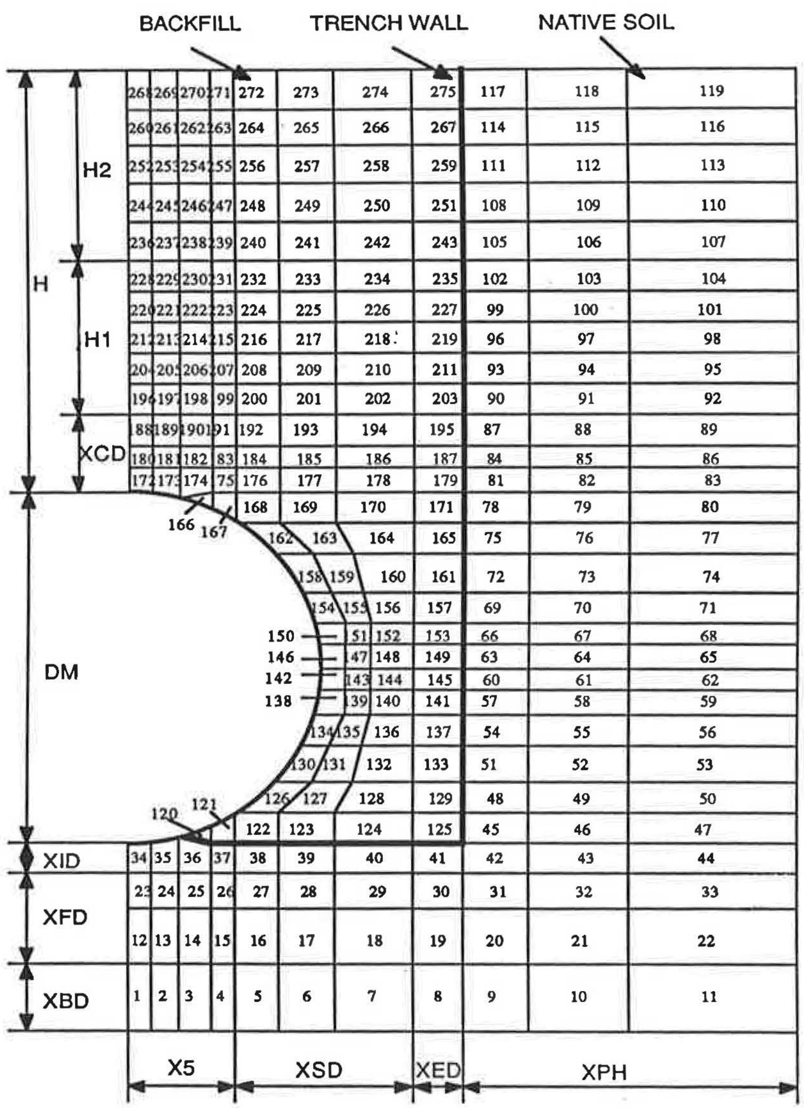


FIGURE 2 Typical finite element mesh used in analyses.

Because of the symmetry, only half of the soil-pipe system was analyzed. Half of the 42-in. vitrified clay pipe was divided into 18 circular curved beam elements and half of the soil was divided into 275 two-dimensional isoparametric soil elements with 318 nodes. To obtain sufficiently accurate results, 14 construction layers were used to simulate the actual construction sequence in the field. Similar finite element meshes were used to model 6- and 21-in. vitrified clay pipes under various installation conditions. The soil load acting on the pipe was calculated from the finite element analyses by adding up the normal and shear stress resultants acting at the centroids of the soil elements over the pipe wall. The soil load was then applied as a concentrated load to the pipe in the simulated three-edge bearing strength test where a structural analysis of the vitrified clay pipe was performed by the computer program under the simulated supporting and loading conditions of the three-edge bearing test. The bedding factor was estimated as the ratio of the maximum tensile strain in the simulated three-edge bearing test to that in the finite element analyses of the soil-pipe system. The maximum strains due to bending occurred at the crown and invert of the pipe in all cases. The ratio of the soil load causing failure in the buried pipe to that load causing failure in the three-edge load test might be a better definition of the bedding factor. Due to the fact that the clay pipe industry is committed to the definition based on strains, the authors used the maximum strains for computing the bedding factors. However, the clay pipe industry relied on comparison of strains for computing the bedding factor because strains were easier to measure than loads on the pipe in both field tests and controlled laboratory tests. Therefore, the strain ratio was selected for defining the bedding factor in the present research. It should be noted that the bedding factors calculated by both methods yield exactly the same results when the strain level is under the failure value of about 500 microstrain.

NEW BEDDING FACTORS

The bedding factors computed by comparing the maximum strains from the finite element analyses with those from the simulated ASTM-specified three-edge loading test are given in Figures 3-17. The variations of the bedding factor with backfill height for 6-, 21-, and 42-in. clay pipes are shown in Figures 3-5. The trench width used for these three figures ranges from 1.5 to 8 ft. The bedding factor depends significantly on the backfill height for the smallest diameter pipe. Even for the large-diameter pipes, the dependence on the backfill height is significant enough to consider this variable as an important parameter governing the choice of the bedding factor in clay pipe design. It is also clear from these figures that the level of compaction and the soil type play important roles in the determination of bedding factors for clay pipe installations. The ASTM-specified bedding factors vary from 1.1 to 2.2, whereas the bedding factors from the finite element analyses vary from 1.6 to 3.6 in these figures. The bedding factor, in general, increases as the backfill height increases. This is probably because the sidefill loading, which can increase the bedding factor (7), increases as the backfill height increases. Due to the fact that the overly celebrated Marston theory makes much of the trench width, the influence of trench width on the bedding factor was studied in great detail in this research program with typical results shown in Figures 6-14. The variations of bedding factor with trench width for three backfill heights are shown in Figures 6-8 for the 6-in. pipe. These figures show that for the small-diameter pipe, the bedding factor decreases as the trench width increases. However, this rate of decrease is somewhat independent of the backfill height but controlled by soil type and compaction density. The variations of bedding factor with trench width are shown in Figures 9-11 for three levels of soil cover depth on a 21-in. pipe. In some cases of soil type, the bedding factor increases with trench width, but in others it decreases with trench width. This inconsistency could be explained by the stiffness and the unit weight of the trench soil in comparison to those of the native soil. In the cases where the soil in the trench is heavier or is only about the same stiffness as that of the native soil, the bedding factor tends to decrease with an increase in trench width. Variations of bedding factor with trench width for three depths of cover are shown in Figures 12-14 for the 42-in. pipe. In almost all cases, the bedding factor increases with trench width. Variations of bedding factor with pipe diameter are shown in Figures 15-17 for three depths of cover. In almost all cases, the bedding factor tends to increase with diameter of the clay pipe.

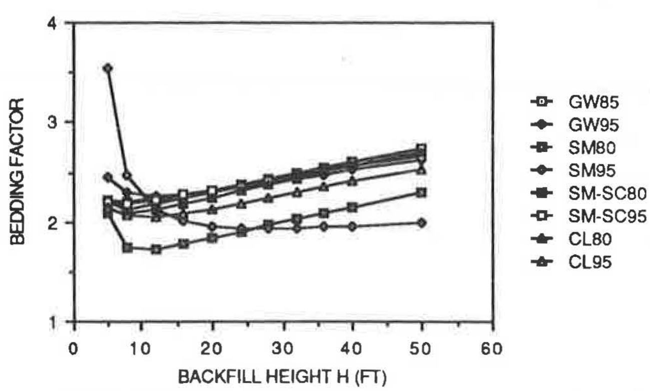


FIGURE 3 Bedding factor versus backfill height: D = 6 in. and B_d = 5 ft.

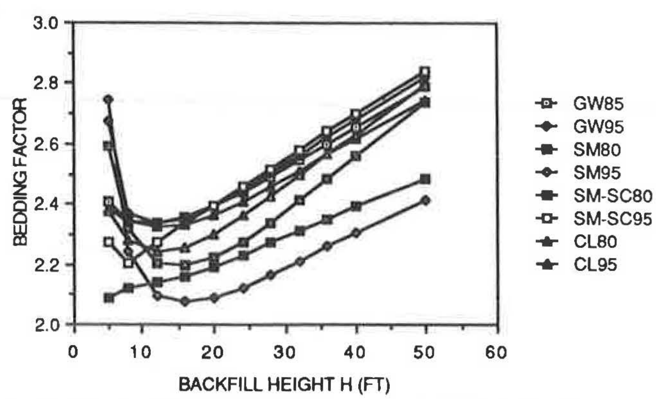


FIGURE 4 Bedding factor versus backfill height: D = 21 in. and B_d = 5 ft.

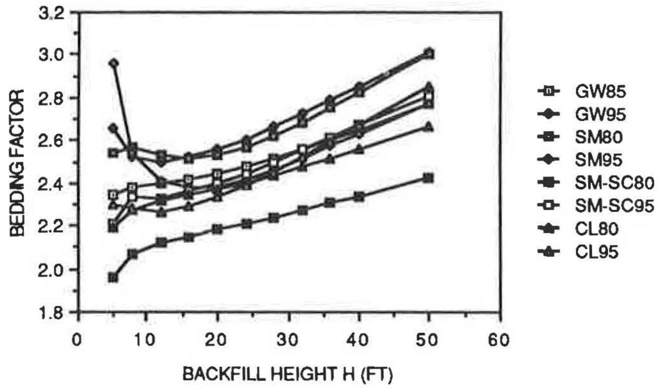


FIGURE 5 Bedding factor versus backfill height: D = 42 in. and B_d = 8 ft.

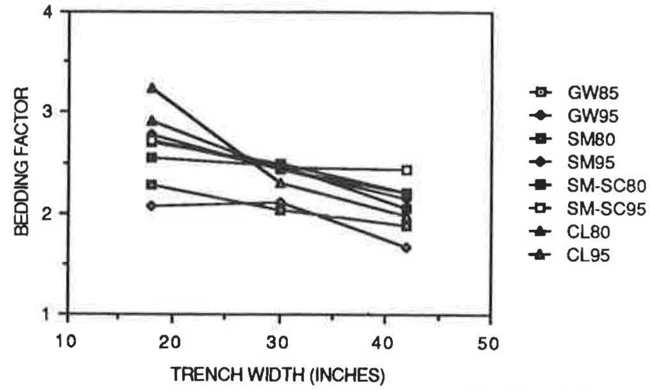


FIGURE 8 Bedding factor versus trench width: D = 6 in. and H = 32 ft.

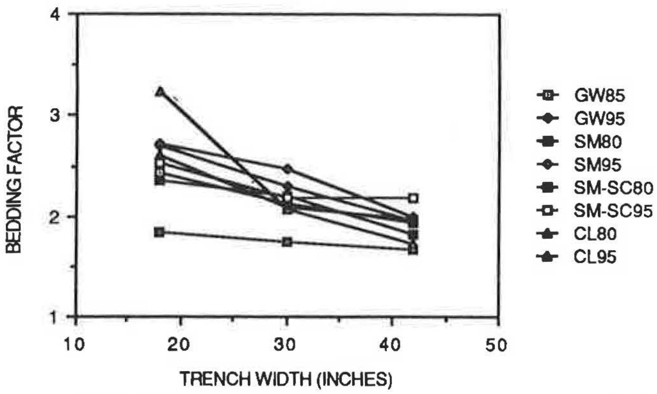


FIGURE 6 Bedding factor versus trench width: D = 6 in. and H = 8 ft.

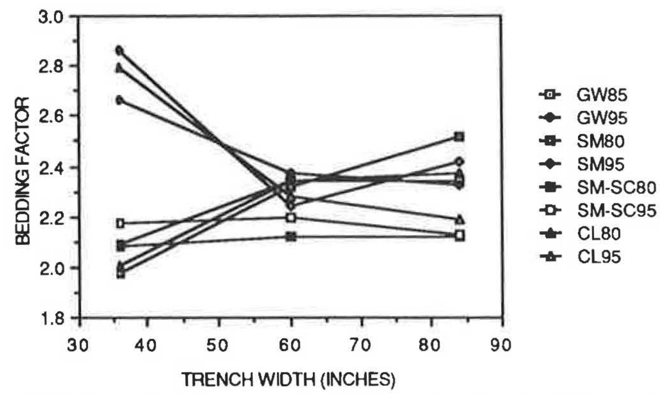


FIGURE 9 Bedding factor versus trench width: D = 21 in. and H = 8 ft.

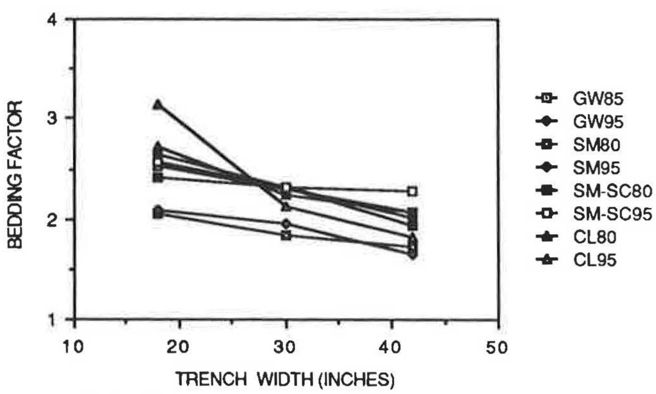


FIGURE 7 Bedding factor versus trench width: D = 6 in. and H = 20 ft.

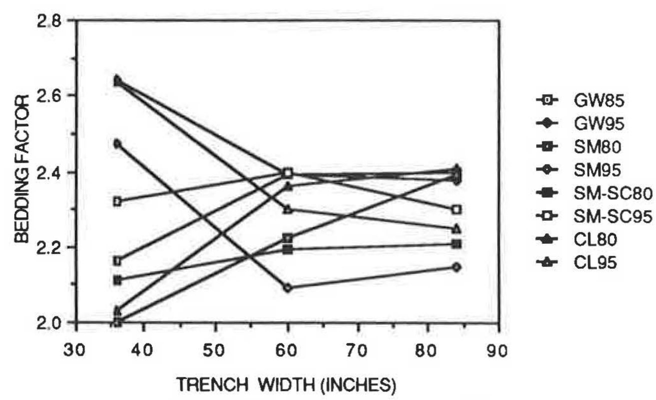


FIGURE 10 Bedding factor versus trench width: D = 21 in. and H = 20 ft.

INTERNATIONAL CLAY PIPE DESIGN PRACTICE

At the conclusion of this research program, the senior author visited a number of clay pipe design engineers and manufacturing facilities in Europe to review the procedures in effect in Europe and other countries for the design of underground clay pipes. During these visits, it was apparent that several countries had abandoned the use of Marston's load theory and its resulting conservative bedding factors. A summary of the bedding factors used by the various countries is given in Table 3. Australia is the only country using compaction density as one of the parameters controlling the choice of the bedding factor used in the design of clay pipes. In the U.S.S.R. bedding factors significantly higher than those in the United States are used. The bedding factor used in the U.S.S.R. for the weakest bedding system is 2.8, which is higher than the 2.2 used in the United States for the strongest bedding system. The loads used by the designers in the U.S.S.R. are also lower than those used in the United States. A review of safety factors used by various countries also

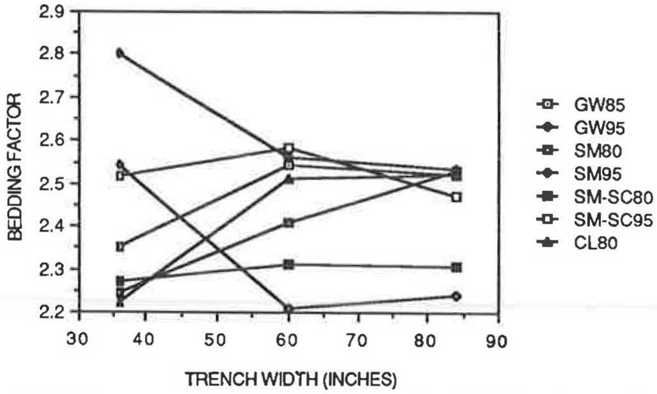


FIGURE 11 Bedding factor versus trench width: D = 21 in. and H = 32 ft.

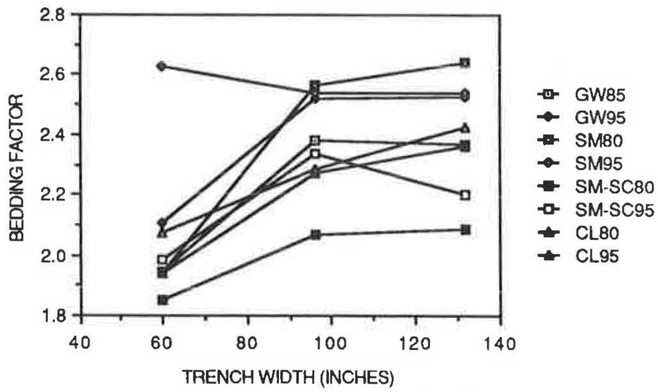


FIGURE 12 Bedding factor versus trench width: D = 42 in. and H = 8 ft.

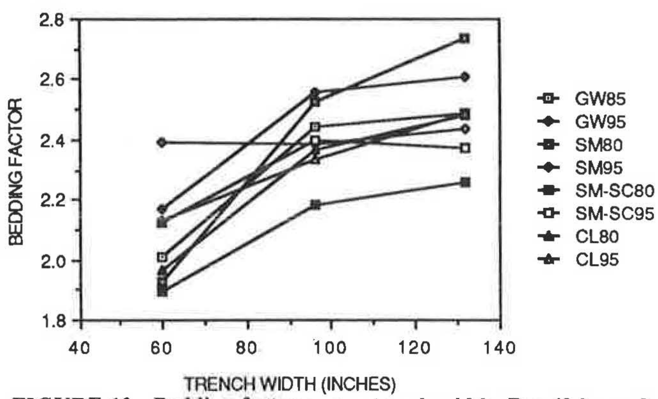


FIGURE 13 Bedding factor versus trench width: D = 42 in. and H = 20 ft.

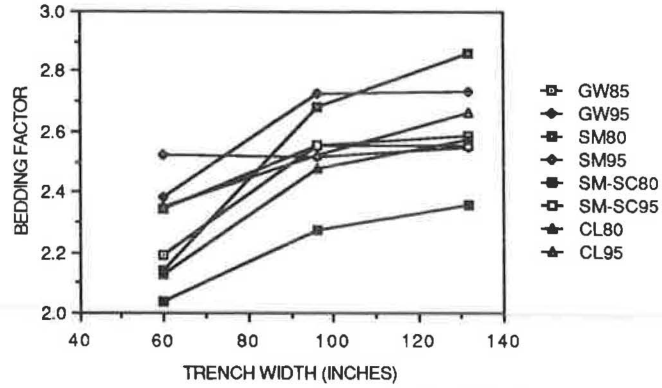


FIGURE 14 Bedding factor versus trench width: D = 32 in. and H = 32 ft.

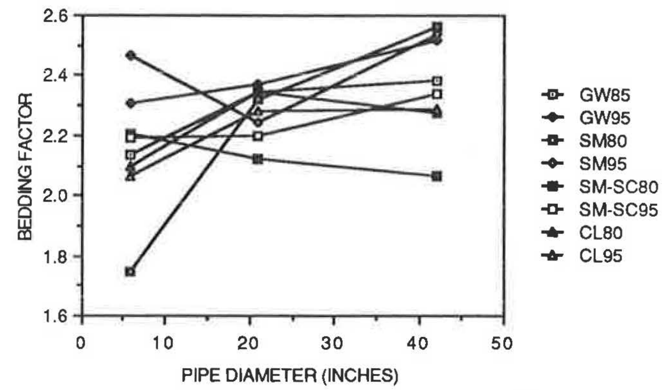


FIGURE 15 Bedding factor versus pipe diameter: H = 8 ft.

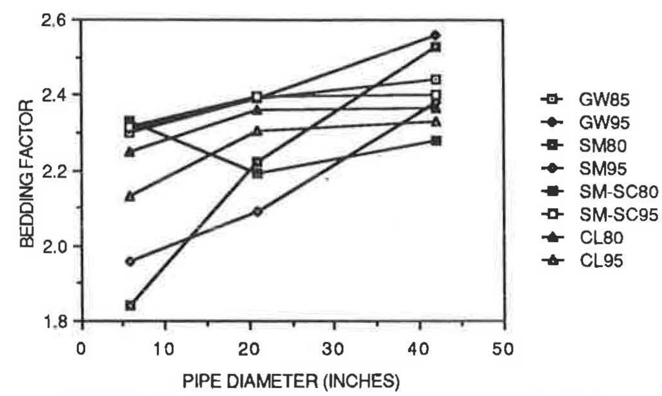


FIGURE 16 Bedding factor versus pipe diameter: H = 20 ft.

revealed some interesting information, as presented in Table 4. In Table 4, the new West German ATV rigorous design method is used as the standard in arriving at the relative margins of safety. In the United States, a factor of safety of 1.5 is used relative to the ATV rigorous method, and in the U.S.S.R., the factor of safety used is 0.9. Switzerland uses a factor of safety of 2.0, but it should be recognized that the loads used on clay pipes are only half as high as those calculated by the Marston load theory.

CONCLUSIONS

Based on the results of this research study, the following conclusions can be made:

1. The bedding factor is dependent on the type of backfill and bedding materials used. Well-graded gravel material gives the highest bedding factors, while silty sand or sand-clay-silt materials give the lowest bedding factors. The degree

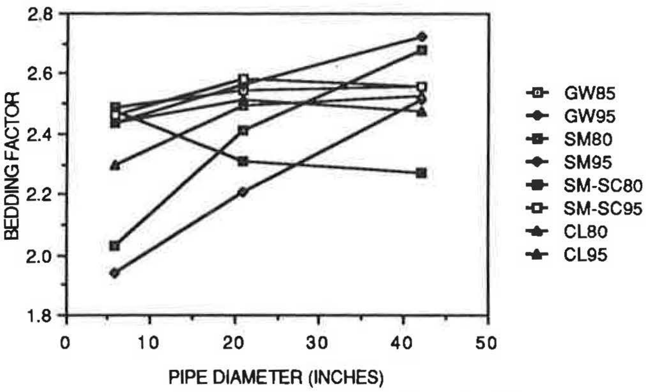


FIGURE 17 Bedding factor versus pipe diameter: H = 32 ft.

of compaction of the backfill and bedding materials is also an important parameter.

2. The bedding factor is affected by the backfill height. The bedding factor generally increases as the backfill height increases.

3. The bedding factor increases with the diameter of the pipe. The trench width also controls the magnitude of the bedding factor to be used in design.

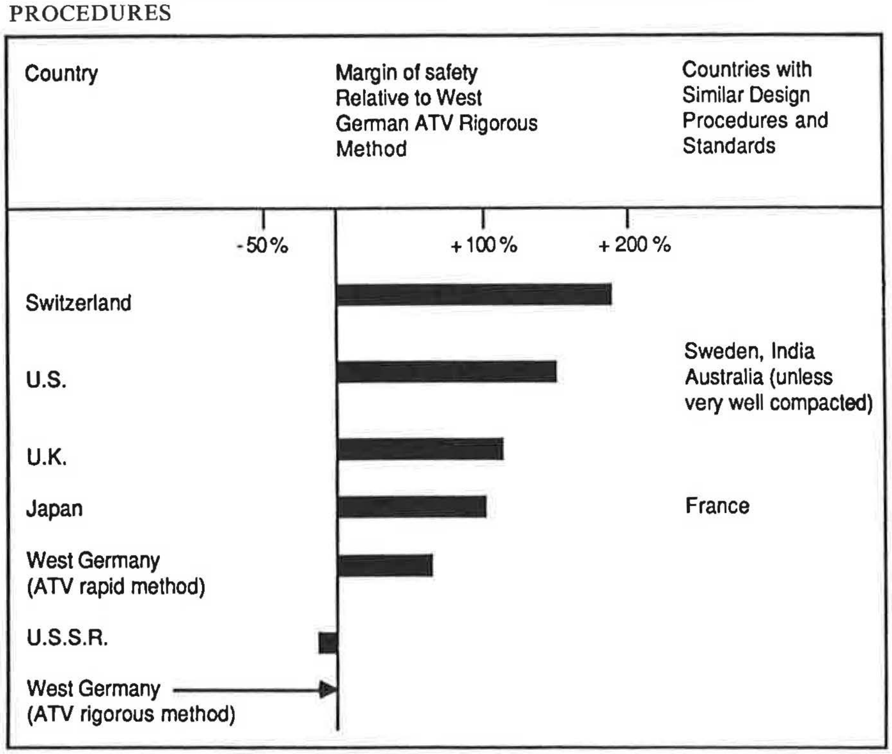
4. The loads used for the design of clay pipes in the United States based on the Marston load theory are too high, and improved loads are given by the authors in another paper elsewhere (*1*). The loads used by several other countries around the world compare better with the loads reported by the authors than with those developed by Marston.

TABLE 3 SUMMARY OF BEDDING FACTORS USED INTERNATIONALLY

Bedding Class	U.K. (Marston load theory)	U.S. (Marston load theory)	Australia (Marston load theory)	India (Marston load theory)	Japan (France) (Marston load theory)	Switzerland (Wetzorke load theory)	W. Germany Clay pipe ind	W. Germany ATV	Russia (Emilianov load theory)	Sweden (Marston load theory)
S	2.2	2.2	/	/	2.31	1.5	/	/	3.2	/
B	1.9	1.9	2.5 - 1.9	1.9	2.03	/	/	2.18	3.1	1.88
C	/	1.5	1.9 - 1.5	1.5	1.68	/	1.5	1.59	3.0	/
D	1.1	1.1	1.1	1.1	1.08	/	/	/	2.8	/

/ Bedding not applicabe.

TABLE 4 RELATIVE MARGIN OF SAFETY FOR VARIOUS DESIGN PROCEDURES



5. The factor of safety used in U.S. practice is also high, particularly when the low bedding factors in effect are taken into consideration. Thus, use of higher bedding factors, lower factors of safety, or lower loads on these vitrified clay pipes are more appropriate. These procedures would enable pipe design engineers to use materials more efficiently while the United States is undergoing a major infrastructure rehabilitation program in many of its oldest cities.

6. Based on the available information, it appears that a bedding factor of 3.5 for crushed stone encasement and 2.5 for Class D beddings could be used when the loads calculated for the pipe are based on Marston theory.

7. Although the research and conclusions thereof are for vitrified clay pipes, the results would also be applicable for concrete pipes with some minor modifications.

ACKNOWLEDGMENTS

The results reported in this paper were obtained as part of an ongoing research program on vitrified clay pipes funded by the National Clay Pipe Institute at the University of Wisconsin, Madison. A major field observation program is being planned at the time of writing this paper to verify the results of the finite element analyses. In this field test program, a series of strain-gauged vitrified clay pipes will be monitored at actual installations under varying backfill and load conditions, and the results will be compared with those obtained from the finite element analyses. The results of this field test program will be reported in another paper at a later date. The technical assistance provided by Edward Sikora and Howard Lund is greatly appreciated. Audrey Miller typed the manuscript.

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APPENDIX

Notations

The following symbols are used in this paper:

B_c = outer diameter of vitrified clay pipes,
B_d = horizontal width of trench at top of vitrified clay pipes,
D = inner diameter of vitrified clay pipes,
H = backfill height,
K_b = bulk modulus number,
K_o = coefficient of earth pressure at rest,
m = bulk modulus exponent,
n = modulus exponent,
R_f = failure ratio,
γ = unit weight of backfill materials,
$\Delta\phi$ = friction angle parameter, and
ϕ = friction angle.