Empirical axial resistances of driven sheet piles

Capacité de charge verticale des cloisons de palplanches

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ABSTRACT

The axial resistance of driven sheet piles has been investigated with extensive statistical analysis of load tests. From the analysis, the base resistance q_b and the skin friction q_s of sheet piles has been derived as a function of the mean cone resistance q_c (CPT) at quantile values. In this paper, the characteristic empirical values of the base resistance and the skin friction of driven sheet piles are presented based on a global concept for axial load capacity of pile systems, which is already integrated in the national German recommendations for piles EA-PFÄHLE (2007). Furthermore, a comparison between the axial load capacities derived from the statistical analysis and calculated according to already existing empirical values is also presented.

RÉSUMÉ

La capacité de charge verticale des cloisons de palplanches était étudiée avec la vaste analyse statistique des essais de charge. On dérive de ces analyses la résistance de pointe q_b et le frottement de couche q_s des palplanches, de façon dépendante de la résistance de pointe de sondage q_c de l'essai de pénétration au cone (CPT) sous des considérations des valeurs quantile. Ici, la résistance de pointe et le frottement de couche sont représentés se basant par les cloisons de palplanches enfoncés, sur un concept global pour la capacité de charge par les systèmes de pieu qui sont déjà intégrés dans les recommandations allemandes nationales pour des pieux EA-PFÄHLE (2007), des valeurs empiriques caractéristiques. En outre, une comparaison entre les charges verticales de l'analyse statistique avec des valeurs calculées pertinentes et les valeurs empiriques existant déjà est représentée.

1 INTRODUCTION

According to German national standard DIN 1054:2005, analytical calculation methods cannot generally be used for the determination of pile resistance, since no methods are available at present, which describes the mechanical model and the influences of the installation method of the different pile systems. Therefore, the resistance-settlement behaviour has to be verified on the basis of pile load tests on the field or comparable pile load test results from the nearby area with similar underground conditions. If no pile load tests are carried out and empirical values from directly comparable load tests are not available, the characteristic axial pile resistance of a single pile can be determined from general empirical values of axial pile resistances according to DIN 1054:2005. Similar specifications can be found in EN 1997-1:2005 (Euro code EC 7-1).

However, very limited empirical values for pile resistance are available for few pile systems in the existing German pile standards DIN 4026, DIN 4014, DIN 4128 and the new DIN 1054:2005. This deficiency in empirical values has been taken as a motive to form a data base of axial pile load tests on different pile systems and analyze them statistically. The goal of the study was to derive a range of empirical value of base resistance and skin friction as much as possible for different pile systems and hence to contribute to the economical evaluation of the axial resistances of piles.

2 STATISTICAL METHODS

The descriptive and statistical methods used for the derivation of axial pile capacity based on empirical values are briefly presented in the following. For details, see Hartung et al. (2002). Beside the descriptive data analysis for the structuring and description of the data using histograms and statistical parameters such as standard deviation, the analytical procedures use the correlation and regression parameters in the analysis.

In the context of the correlation analysis, the relationships are represented in the form of scatter plots and are evaluated qualitatively using the coefficient of correlation. Moreover, comparisons had been made between the correlations of different attributes.

Based on the qualitative relationships of the correlation analysis, a regression model has been developed and validated using the available data. The regression analysis specifies the functional relationship between a dependent and one or more independent variables and it makes the empirical representation of larger data

Table 1. Statistical parameters

variable	x_i, y_i
arithmetic average	$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$ (1)
standard deviation	$s = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2}$ (2)
coefficient of correlation	$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x}) \cdot (y_i - \bar{y})}{(n-1) \cdot s_x \cdot s_y}$ (3)

Table 2. Pile systems

Driven precast piles	(e.g. reinforced and pre-stressed concrete piles, steel piles)
Driven cast in place piles	(e.g. Franki-type piles, Simplex-type piles)
Screwed cast in place piles	(e.g. Atlas piles, Fundex piles)
Micro piles	

and consequently the interpolation of missing values as well as prediction of future values possible through an iterative optimization of the regression model.

3 PILESYSTEMS AND DATABASE

Data are collected mainly from static but also from dynamic load tests of different pile systems (Table 2) and they are compiled in a data base.

In the derivation of the axial pile resistance, only those pile load test results that have adequate information on the underground conditions, are exclusively used in order to attain a reliable correlation between the soil strength properties and the pile resistance. Altogether about 1000 pile load test results of the different pile systems had been compiled in the data base, see also Kempfert & Becker (2007).

4 EMPIRICAL PILE RESISTANCES

4.1 *Determination of pile resistances*

The characteristic axial bearing capacity of a single pile is given by

$$R = R_b + R_s = q_b \cdot A_b + \sum_{i=1}^{n} \left(q_{s,i} \cdot A_{s,i} \right) \quad (4)$$

where:

A_b area of pile base;
$A_{s,I}$ area of pile shaft in layer i;
q_b base resistance;
$q_{s,I}$ skin friction in layer i.

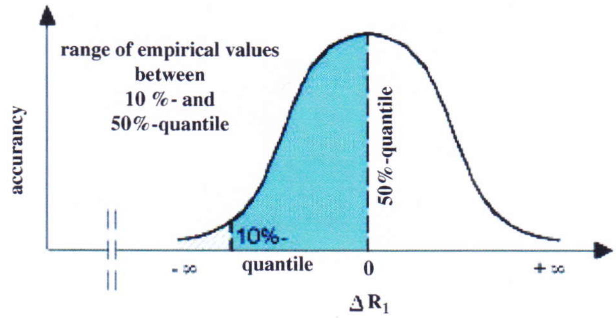

Figure 1. Range of empirical Values of pile.

Depending on the qualitative relationships between soil strength and base resistance and/or skin friction of the correlation analysis, a regression model is developed that take into account the proportion the two components of the axial pile bearing capacity. In the regression analysis, the functional relationships between axial pile load capacity and soil strength had been optimized iteratively until the difference between measured and calculated axial pile load capacity becomes or approaches to zero:

$$\Delta R_1 = \frac{R_{1,m} - R_{1,cal}}{R_{1,m}} \equiv 0 \quad (5)$$

where:

ΔR_1 Difference between measured and calculated axial pile resistance for the ultimate limit state (ULS),
$R_{1,m}$ Measured value of the axial pile resistance from pile load tests,
$R_{1,cal}$ Calculated value of the axial pile resistance according equation (4).

To construct the load-settlement-curve, settlement dependent empirical values are derived for base resistance and skin friction. The settlement criteria differs depending on the installation method of the piles (Kempfert & Becker 2007; Witzel 2004). In the statistical analysis, the empirical values of the axial pile resistance for the ultimate limit state (ULS) are first determined and then the empirical values for settlement dependent resistances are derived in further analysis steps. In this way the load-settlement-curve can be constructed and thus the serviceability limit state (SLS) can be verified.

4.2 *Range of empirical Values*

According the German national standards DIN 1054 and DIN 4020, the soil strength parameters can scatter substantially due the boundary conditions of the geological process. This applies in particular to the pile load bearing behaviour in ULS and SLS, because beside the scatter in the soil strength parameters, additional influences of the installation method will come to question.

Since the empirical values for the pile resistance are available for few pile systems in a very limited amount, the scatter of pile bearing capacity can be considered in the statistical analysis by using a range of quantile values as shown in Figure 1.

In the present analysis, empirical values for pile resistance have been derived at 10%, 20% and 50%

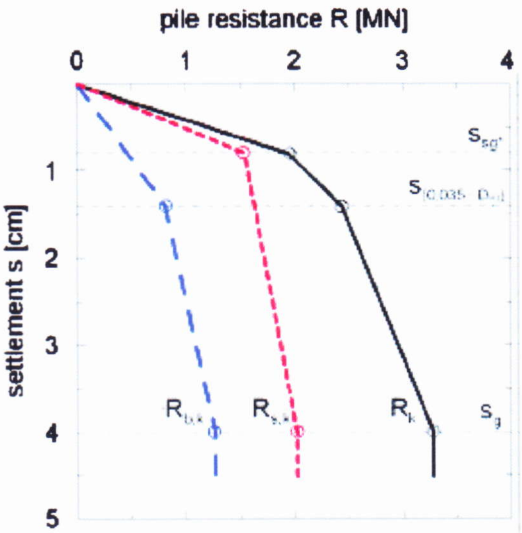

Figure 2. Idealized load-settlement-curve for driven precast piles.

quantiles. A 10% quantile means that 90% of the cases of the empirical determination of the axial pile resistance lies on the safe side and/or does not exceed the existing measured resistances. Unlike conservative average values at 50% quantile are usually taken for determination of the characteristic soil properties.

The range of empirical values indicated in Figure 1 can vary depending on pile load tests and local boundary conditions and it only serves as first orientation.

4.3 *Empirical Values of axial pile resistances for driven precast piles*

Taking displacement piles, i.e. driven precast piles, as an example, the derivation of pile resistances on empirical basis is described in the following.

For the construction of load-settlement curves for driven precast piles, Witzel 2004 recommends settlement dependent base resistance at $s/D = s/D_{eq} = 0{,}035$ and skin friction at failure state. The settlement dependent skin friction at failure has been modified in this study as follows:

$$s_{sg} = 0.5 \cdot R_{s1} \leq 1.0\ cm \tag{6}$$

The proportion of the pile base resistance R_b to skin friction R_s of the total pile capacity developed by Witzel (2004) based on laboratory model tests has been modified using results of well instrumented static pile load tests, dynamic load tests, both compression and tension load tests. Moreover, a distinction has to be made between the skin friction R_s (g) with $s = s_g = s_{sg}$ at failure and the mobilization of the skin friction R_s (sg*) at failure with $s = s_{sg*}$ for driven precast piles, which are introduced as a supplement in this study. Considering a settlement dependent skin friction, the load-settlement-curves can be drawn for driven precast piles as shown in Figure 2.

To consider all type of precast driven piles uniformly, equation (4) is extended by introducing adjustment factors to the base resistance and skin friction. The characteristic axial bearing capacity of a precast driven piles is therefore given by:

$$R_k(s) = R_{b,k}(s) + R_{s,k}(s) = \eta_b \cdot q_{b,k} \cdot A_b + \eta_s \cdot \sum_{i=1}^{n} \left(q_{s,k,i} \cdot A_{s,i}\right) \tag{7}$$

where:

η_b adjustment factor for base resistance, here $\eta_b = 1.0$;
η_s adjustment value for skin friction, here $\eta_s = 1.0$.

Table 3. Empirical base resistances of driven precast piles in non-cohesive soils for ULS

$s/D_{eq} = 0{,}1$	Base resistance $q_{b1,k}$ [kN/m^2]		
	Mean cone resistance q_c [MN/m^2]		
	7.5	15	25
10%-quantile	4200	7600	8750
20%- quantile	4500	8300	9500
50%- quantile	6000	10200	11500

Table 4. Empirical skin friction values of driven precast piles in non-cohesive soils for ULS

$s_{sg} = s_g = 0{,}1D_{eq}$	Skin friction $q_{s1,k}$ [kN/m^2]		
	Mean cone resistance q_c [MN/m^2]		
	7.5	15	25
10%-quantile	40	95	125
20%- quantile	45	105	140
50%- quantile	60	125	160

For driven precast piles, settlement dependent resistances are also to be considered for the construction of the load-settlement-curves (Kempfert & Becker 2007; EA-PFÄHLE 2007).

4.4 *Empirical adjustment factors for driven Sheet Piles*

The adjustment factors in equation (7) for base resistance and skin friction of driven precast piles are presented in the following. The analysis of sheet piles is made on the basis of the base resistance and skin friction values determined for driven precast piles. In order to apply these values to the driven sheet piles, empirical adjustment factors η has been derived in the following.

The determining reference areas for skin friction and base resistance are shown Figure 3. The steel cross-sectional area is determining for the base resis-

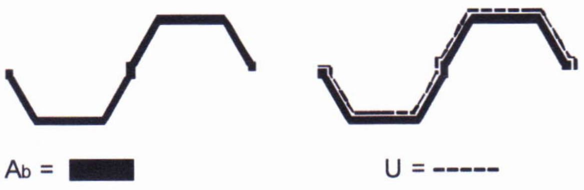

Figure 3. Reference areas for determining end bearing resistance an skin friction of sheet piles.

Table 5. Empirical adjustment factors for driven sheet piles and the proportion of skin friction to the total pile resistance

	R_s/R_1 [%]	R_s/R_1 [%]
load tests	80.0	20.0
$\eta_b = 1.30$ and $\eta_s = 0.90$	87.0	13.0

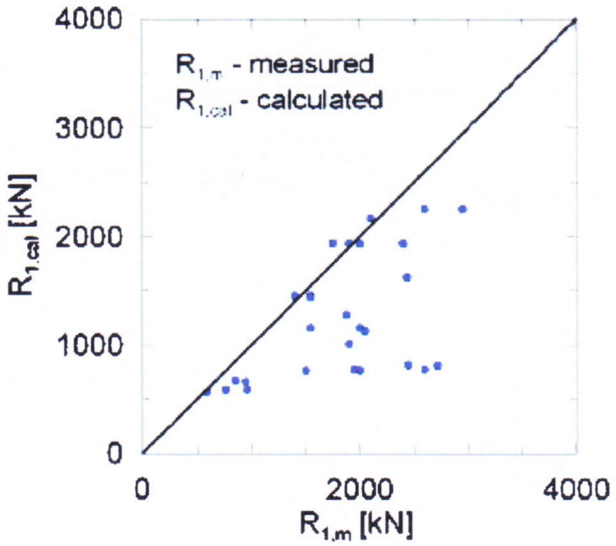

Figure 4. Scatter plot for 10%-quantile of driven sheet piles.

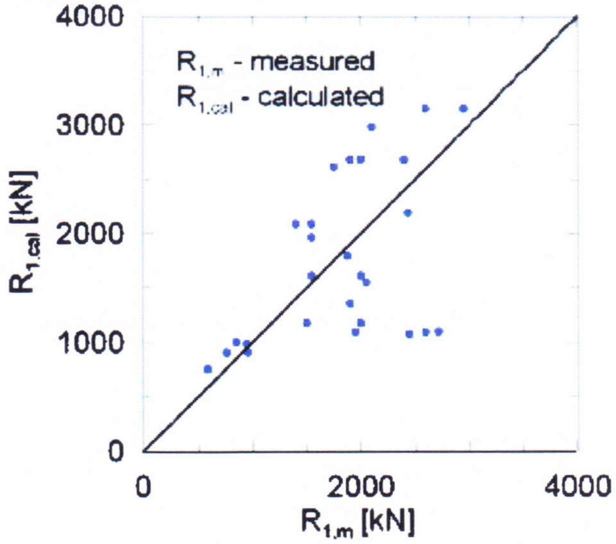

Figure 5. Scatter plot for 50%-quantile of driven sheet piles.

tance, whereas the outer surface area denoted as U in Figure 3 is used for skin friction. Due to restraining and plugging effects depending on the geometry of the sheet pile profile, the inner surface area will be included in the statistical analysis through the adjustment factor η_s according to equation (7).

The skin friction part of the pile resistance are slightly increased using the adjustment factors in Table 5 based on dynamic load tests and the concept of the bearing behaviour of pile systems according to Kempfert & Becker (2007).

The results of statistical analysis are summarized in Figure 4 to 6 as well as in Table 6.

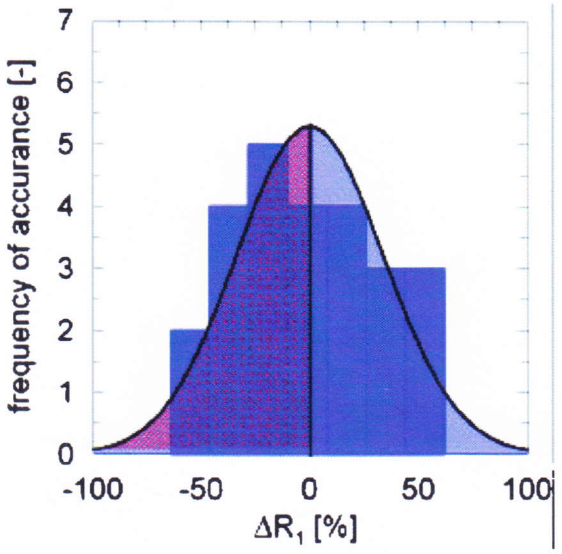

Figure 6. Histogramm for 50%-quantile of driven sheet piles.

Table 6. Statistical results for sheet piles with, $\eta_b = 1{,}3$ and $\eta_s = 0{,}9$

	ΔR_1 [%]	s [%]	r [-]
10%-quantile	0.2	33.9	0.46
20%- quantile	−9.0	28.2	0.46
50%- quantile	−2.0	24.5	0.48

Table 7. Sheet piles – cross sections (double blank)

type	b [m]	h [m]	$A_{b,Steel}$ [m^2]	U [m]	α [°]
Hoesch 1200	1.15	0.26	0.016	0.150	50
Larssen 703K	1.40	0.40	0.018	0.203	46

4.5 *Empirical axial resistance of driven sheet piles*

The resistance of driven sheet piles derived based on empirical values for driven precast piles and the corresponding adjustment factors for driven sheet piles are represented in Figures 7 and 8.

For comparison purpose, empirical resistance values for driven precast piles according to EA-PFÄHLE (2007) and DIN 1054:2005 are also shown in Figures 7 and 8.

5 COMPARISON OF EMPIRICAL VALUES FOR DRIVEN SHEET PILES

The predicted axial pile resistances R_1 according to equation (7) for driven sheet piles are compared with the measured results in Figure 9 for a sheet pile profile type Hoesch 1200 and in Figure 10 for type Larssen 703 as a function of embedment depth. For the analysis of the axial pile resistance, the German recommendation for excavations (EAB 2006)) and waterfront structures, harbours and waterways (EAU 2004) has also been consulted.

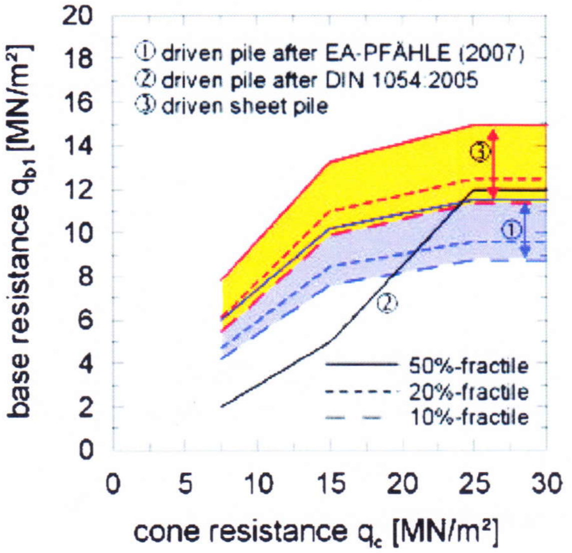

Figure 7. Empirical base resistance q_b for driven sheet piles in non-cohesive soils.

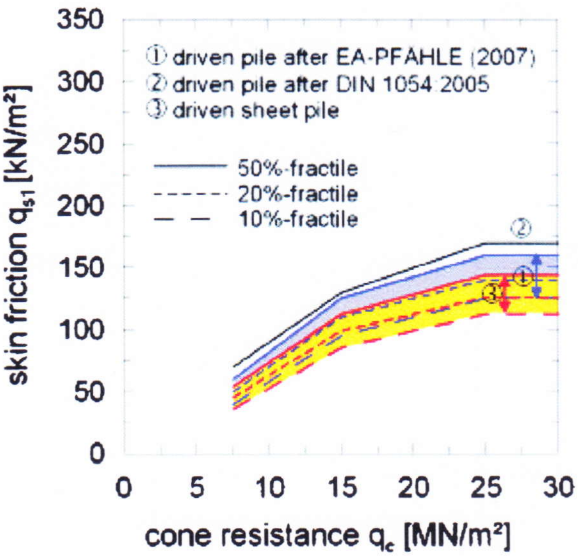

Figure 8. Empirical skin friction q_s for driven sheet piles in non-cohesive soils.

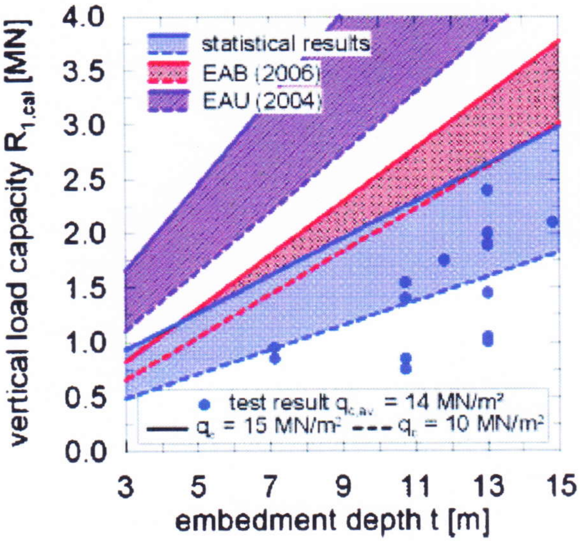

Figure 9. Vertical load capacity for drive sheet piles, Typ HOESCH 1200.

According to EAB (2006), the determination of the axial resistance based on empirical values follows the recommendation by Radomski (1968) and Weißenbach (1977), where the pile base area is reduced by a factor depending on the sheet pile geometry as follows:

$$A_b = \kappa \cdot h \tag{8}$$

where

κ: adjustment factor after Radomski (1968)
h: height of the sheet pile profile

Then, the axial resistance of driven sheet piles is given by:

$$R_{1,k} = A_b \cdot q_{b1,k} + A_s \cdot q_{s1,k} = A_b \cdot (600.0 + 120.0 \cdot (t_g - 0.5)) + A_s \cdot 60.0 \tag{9}$$

where t_g is the real embedment depth.

For cone resistance $q_c > 10.0$ MN/m, the axial resistance of sheet piles from equation (9) has to be corrected. For example, the pile resistance can be increased by 25% for $q_c = 15.0$ MN/m².

According to EAU (2004), the axial resistance of driven sheet piles can be determined using equation (4) based on the empirical values given in DIN 1054:2005 which are dependant on the mean cone resistance of the underground (see also Figures 7 and 8). The base area used for calculation of the base resistance is assumed to be a multiple of the steel cross-sectional area, i.e.

$$A_b = n \cdot A_{b,Steel} = (6\,to\,8) \cdot A_{b,Steel} \tag{10}$$

The derived empirical values for pile resistances show a good agreement with the measured values for 50%-quantile as shown in Figures 9 and 10.

The axial resistances of driven sheet piles based on empirical values are shown in Figures 9 and 10 as a function of the embedment depth in the bearing strata for a homogeneous soil with $q_c = 10.0$ and 15 MN/m². To compare the results directly, the measured values

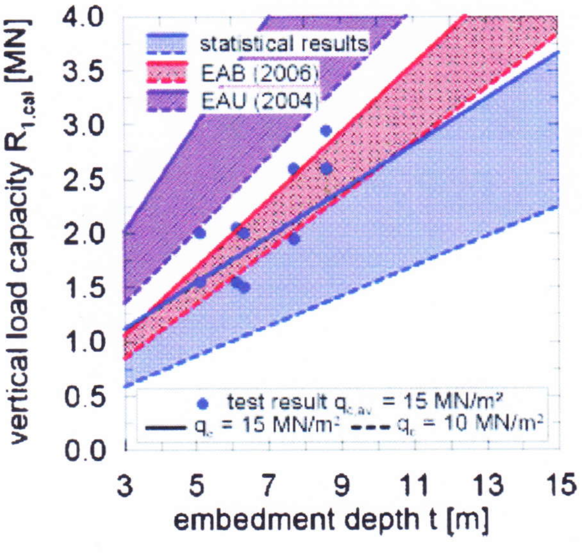

Figure 10. Vertical load capacity for drive sheet piles, Typ Larssen 703 K.

are also indicated in Figures 9 and 10 for a mean con resistance $q_{c,av} = 15.0\,MN/m^2$.

The axial pile resistance based on empirical values according to EAU (2004) and DIN 1054:2005 shows a large deviation from the measured values compared to the empirical values derived in this study and the values according EAB (2006) (Figures 9 and 10).

6 CONCLUSION

The study provides to a large extent a secured range of empirical values for the base resistance and the skin friction for driven sheet piles as a function of mean cone resistance. Based on comparative statistical analysis of pile load tests of different pile systems, it becomes possible to derive a consistent analysis of bearing behaviour of pile systems, which provides a safe and maybe economical pile bearing capacity depending on the expense of preliminary soil investigations.

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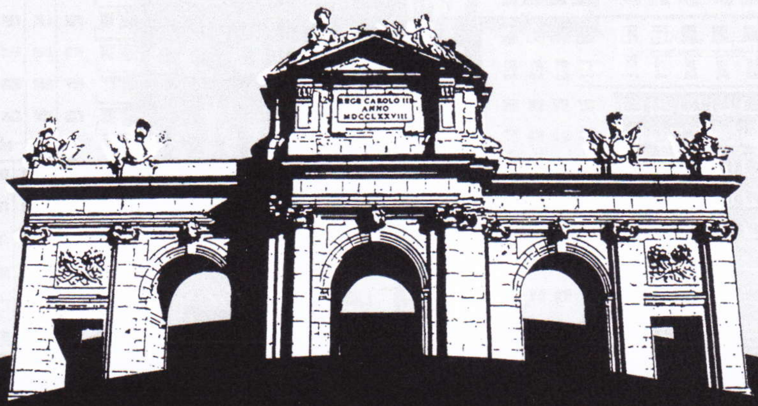

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