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ARCHAEOLOGY AND ENGINEERING: THE FOUNDATIONS OF AMIENS CATHEDRAL

(*with five figures*)

The significance of Gothic architecture resides in its extraordinary integration of structural and aesthetic innovation. As an architectural style, it broke decisively with Roman and Roman-derived forms to evolve new wall configurations with increased fenestration set within taller structural systems. These innovations have consistently attracted scholarly attention, of which a significant portion has been devoted to explanations of structural elements such as rib vaults and flying buttresses. However, the attention paid to the innovative technology of Gothic architecture has rarely extended to include the foundation systems which support these buildings. Despite their obvious functional importance in relation to increasingly taller buildings, and their crucial position as the earliest built phase of a new building's design, foundations have been largely ignored in architectural scholarship, and omitted from most published section drawings.

Those few studies which have treated foundations have attempted to trace the presumed formal evolution of foundation walls (H. Bernard, "Essai sur la genèse des fondations gothiques," *Cahiers archéologiques de Picardie,* 1975, pp. 85—100). However, this approach ignores the crucial relationship between any foundation and the geology of its building site. The function of a foundation is to distribute the load of the building's superstructure to an area of supporting soil or rock so as not to exceed the latter's capacity to carry that load. Buildings do not simply rest *on* the ground, but rather they interact with the soil below. Thus, analysis of medieval foundation systems must account for geological factors as well as structural principles. To take one example, analysis of the foundations beneath Amiens Cathedral reveals that medieval builders were aware of local site geology and that they used it to plan the substructure of their building.

Beneath the floors of Notre-Dame d'Amiens, a stepped, interlocking grid of below-ground walls rest on an evidently continuous raft of mortared stone. Our knowledge of Amiens comes from excavations carried out sporadically between 1850 and 1897, first under the direction of Eugène Viollet-le-Duc and then from 1874, under Just Lisch. As no report of the excavations seems ever to have been published, one must rely on two textual sources: Viollet-le-Duc's discussion of the footing below a pier buttress (*Dictionnaire*, IV, p. 175) [*Fig. 1*] and Georges Durand's plan and elevation of a section through the northern half of the choir (*Monographie*, I, pp. 202—204) [*Fig. 2*]. From these two brief descriptions, it is unclear how extensive an area of the Amiens foundations was actually revealed. At a minimum, one bay in the choir side-aisle and an area between the buttresses must have been opened, but a much larger area may have been excavated since Durand indicates that the paving was taken up in the choir (p. 202).

In spite of these limitations, there is far more information about the foundations beneath Amiens Cathedral than is available for most large Gothic structures. In the *Dictionnaire* (see *Fig. 1*), Viollet provides a description of the form, stone types, depth and soil conditions for a pier buttress of the choir at Amiens: *En A, est une couche de terre à brique de 0,40 c. d'épaisseur posée sur l'argile vierge; en B, est un lit de béton de 0,40 c. d'épaisseur; puis, de C en D, quatorze assises de 0,30 à 0,40 c. d'épaisseur chacune, en libages provenant des carrières de Blavelincourt près d'Amiens. Cette pierre est une craie remplie de silice, très-forte, que l'on exploite en grands morceaux. Au-dessus, on trouve une assise E de pierre de Croissy, puis trois assises F de grès sous le sol extérieur. Au-dessus du sol extérieur, tout l'édifice repose sur six autres assises G de grès bien parementées et d'une extrême dureté. Derrière les revêtements de la fondation est un blocage de gros fragments de silex, de pierre de Blavelincourt et de Croissy, noyés dans un mortier très-dur et bien fait. C'est sur ce roc factice que repose l'immense cathédrale.* (IV. 175—176)

Durand published a larger plan and section and provided a fuller description of the extent and depth of the excavations at Amiens: *Les fouilles faites jadis par Viollet-le-Duc à l'extérieur de l'édifice, celles qui furent faites en 1894 et 1897 lors de la réfection du dallage et surtout de la construction d'un caveau pour les évêques dans la travée 21, 23 bc, permettent de se rendre compte d'une façon à peu près complète de la disposition des fondations de la cathédrale d'Amiens. Elles sont aussi colossales que le monument lui-même.... Construites à la manière d'un immense radier, elles assurent à celui-ci une assiette inébranlable et une solidité de nature à défier toutes les causes de destruction. En voici le plan et la coupe sur la travée 21, 23 du choeur.*

Le terrain sur lequel s'élève la cathédrale est remblayé sur une hauteur d'environ 7 à 9 mètres au-dessus du bon sol, remblai bien antérieur au XIIIe siècle. Dans toute l'étendue de la surface de l'édifice, ce remblai a été entièrement creusé jusqu'au sol vierge. Sur celui-ci on a étendu, aussi très probablement dans toute la surface de l'édifice, un massif de moëllonage noyé dans le mortier C D E F, plus ou moins épais suivant la déclivité du terrain, de manière à obtenir une surface horizontale à environ cinq mètres au-dessous du sol de l'église.

Sur ce massif gigantesque, véritable roc factice, sont établis de chaînages de pierre G longitudinalement sous les murs extérieurs et sous les lignes des maîtres piliers et

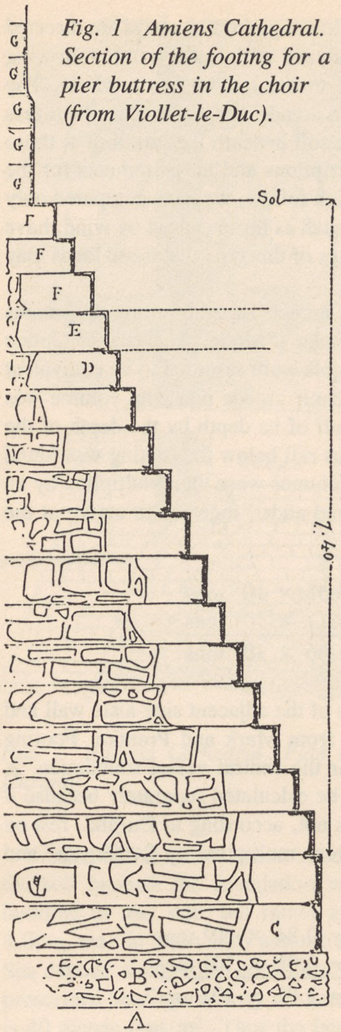

Fig. 1 Amiens Cathedral. Section of the footing for a pier buttress in the choir (from Viollet-le-Duc).

transversalement entre chaque travée, formant ainsi un vaste grillage de maçonnerie, aux intersections duquel s'élèvent tous les piliers. Ces chaînages s'élèvent presque jusqu'au sol actuel, c'est-à-dire sur une profondeur de près de cinq mètres. Epais d'environ 2m, 40 à leur sommet, ils se composent de gros moëllonages parementés de onze assises de libages de pierre que l'on croit être de Blavelincourt mais qui doit être plutôt de Belleuse, très dure et très ferme, d'environ 40 centimètres de hauteur d'assises, descendant avec des ressauts de 15 à 16 centimètres d'empattement jusqu'au massif plein. A chaque intersection, les angles sont renforcés à la partie supérieure des chaînages, en forme de goussets, de manière à donner aux piliers une assiette octogonale. Vers l'extérieur, les gradins de libages descendent jusqu'au bon sol, pour arrêter et soutenir le massif général, et les assises supérieures sont en grès. (I. 202—204.) The combined information of Viollet-le-Duc's and Durand's descriptions and illustrations provide the basis for a quantitative assessment of the foundations of Amiens Cathedral within their geologic context.

The stability of Amiens Cathedral may be understood by comparing the bearing pressure due to the building's weight with the corresponding bearing capacity of the supporting soil. Bearing pressure (BP) is calculated by dividing the building weight supported by a footing by the area at the base of the footing:

$$\text{BP (in metric tons/m}^2\text{)} = \frac{\text{weight in tons}}{\text{area at base (m}^2\text{)}}$$

The bearing capacity of a soil (the maximum soil pressure corresponding to acceptable foundation settlement) is today determined from on-site tests. Modern values typically range from a high of 1000 tons/m^2 for massive rock, to a low of 10 tons/m^2 for footings set on soft clays. When bearing pressures exceed the prescribed values for particular soils, the building structure is put at risk and may even be subject to catastrophic failure.

The calculations required for foundation analysis of buildings like Amiens can be simplified by using a standard engineering approach which takes advantage of the modular nature of medieval construction. Because all loadings from the bays are directed onto the piers and buttresses, these can then be analyzed individually and, following engineering practice, the results can be generalized to the building as a whole. The relationship between the bearing pressure of one main arcade pier and one pier buttress of Amiens Cathedral and the bearing capacity of the soil beneath the building at those points can thus be discussed from available soil descriptions and measurements for the superstructure and foundation. In the calculations which follow, we have computed only dead weight loadings and soil pressures. Live loads, such as those caused by wind, have small enough effect on foundation behavior in buildings of this type that those loads may be neglected.

The total weight at the base of one pier of the arcade superstructure at Amiens Cathedral was taken from R. Mark and R. A. Prentke ("Model Analysis of Gothic Structure, "*JSAH*, 27, 1968, pp. 44—48). Choir weights were assumed to be equivalent to those of the nave. For the foundation beneath a choir arcade pier, the volume was estimated by multiplying the area of the footing at half of its depth by the depth of the stepped footing. [*Fig. 3*] The volume of the continuous raft below the footing was found by multiplying its area by the raft thickness. These volumes were then multiplied by an average density for limestone taken as 2400kg/m^3 and added together to arrive at the total weight:

arcade superstructure weight	$= 0.55 \times 10^3$ tons
arcade foundation weight	$= 1.11 \times 10^3$ tons
total weight	$= 1.66 \times 10^3$ tons

For the total weight of a pier buttress, and portions of the adjacent side-aisle wall and flying buttresses, calculations were similarly taken from Mark and Prentke. Footing weights were found following the approach used for the central vessel foundation. A portion of the footing below the pier buttress had to be calculated separately because it steps continuously downward to natural soil and does not, according to Durand, rest on the continuous platform. [*Fig. 4*] These volumes were multiplied by 2400kg/m^3 and combined to arrive at total weight.

pier buttress superstructure weight	$= 0.84 \times 10^3$ tons
pier buttress foundation weight	$= 0.98 \times 10^3$ tons
total weight	$= 1.82 \times 10^3$ tons

The bearing pressure under the footings of Amiens Cathedral can now be calculated by dividing the total weight by the respective area at the base of the footings:

$$\text{BP (pier)} = \frac{\text{total weight}}{\text{area at base}} = \frac{1.66 \times 10^3 \text{ tons}}{70 \text{ m}^2} = 23.7 \text{ tons/m}^2$$

$$\text{BP (buttress)} = \frac{1.82 \times 10^3 \text{ tons}}{71 \text{ m}^2} = 25.6 \text{ tons/m}^2$$

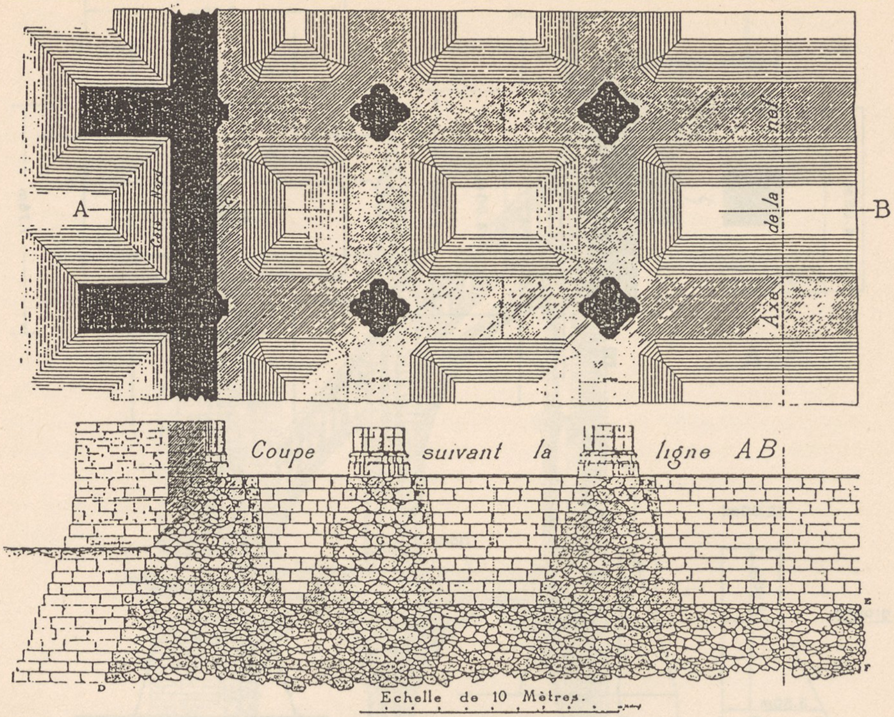

Fig. 2 Amiens Cathedral. Plan and section of the foundations in the choir (from Durand).

Viollet-le-Duc's excavation beside the pier buttress at Amiens Cathedral revealed that the soil beneath the foundation was not the bedrock one might have expected in a building of that size, but rather an „argile vierge". At a subsurface depth of nearly 8.00m, we can reasonably assume that the natural clay Viollet discovered was a Tertiary Sea deposit already pre-consolidated from the weight of its water overburden. Modern prescribed bearing capacity for hard clays, such as those deposited beneath ocean floors, is 40 metric tons/m^2. Thus the bearing pressure of Amiens Cathedral falls reasonably within the soil's capacity to carry the building.

Several important observations may be suggested from our analysis of Amiens Cathedral. First, the structure at Amiens is remarkable for its efficient use of the clay soil supporting it. By our calculations, the building uses about 60 % to 65 % of the allowable bearing capacity of the clay. Second, the bearing stress exhibited beneath the choir pier and that beneath the pier buttress are remarkably close, 23.7 and 25.6 tons/m^2 respectively. The similarity of these stresses is one of the factors which has undoubtedly minimized the risk of differential settlement in a stone building the size of

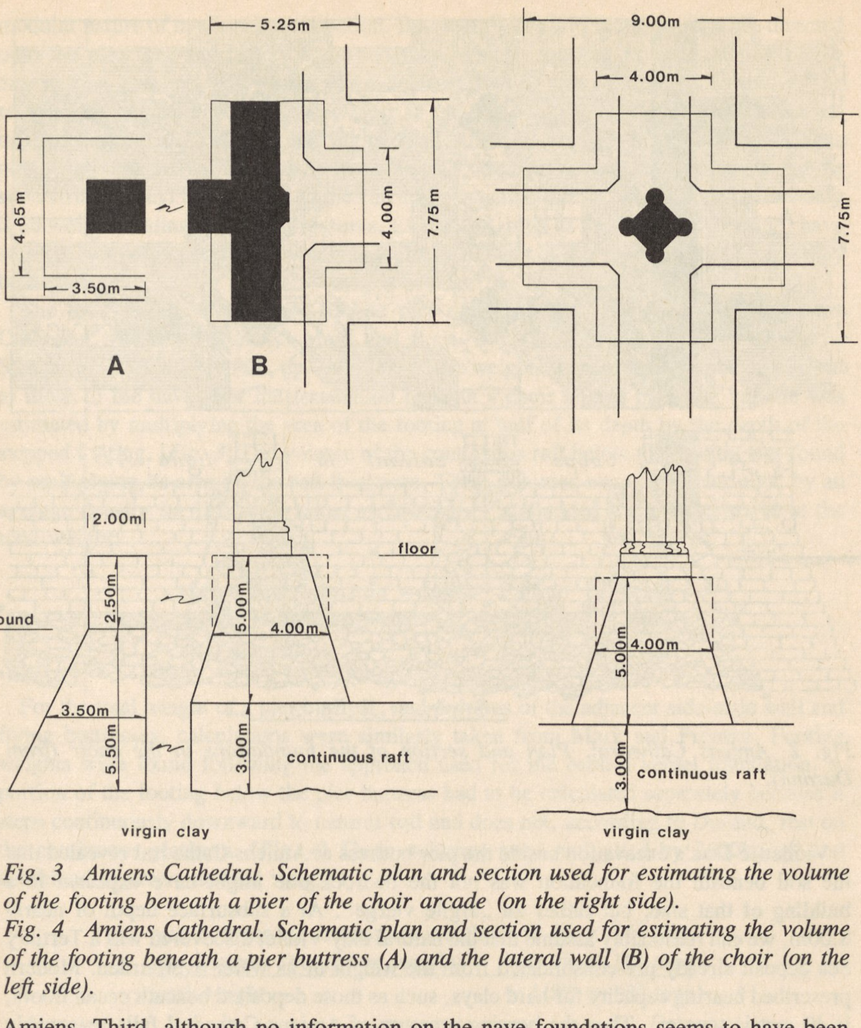

Fig. 3 Amiens Cathedral. Schematic plan and section used for estimating the volume of the footing beneath a pier of the choir arcade (on the right side).
Fig. 4 Amiens Cathedral. Schematic plan and section used for estimating the volume of the footing beneath a pier buttress (A) and the lateral wall (B) of the choir (on the left side).

Amiens. Third, although no information on the nave foundations seems to have been recovered during the 19th-century excavations at Amiens, the results presented here provide technological evidence which supports our hypothesis that they must be comparable to the foundations in the choir. Fourth, the foundations themselves are of such enormous size and weight that their construction would have revealed any problems of instability or differential settlement *before* work on the superstructure began.

A number of provisional conclusions about medieval building practice may also be suggested from this analysis. It would seem that the medieval builders had good understanding of the advantage of distributing the load of a tall building over a wide

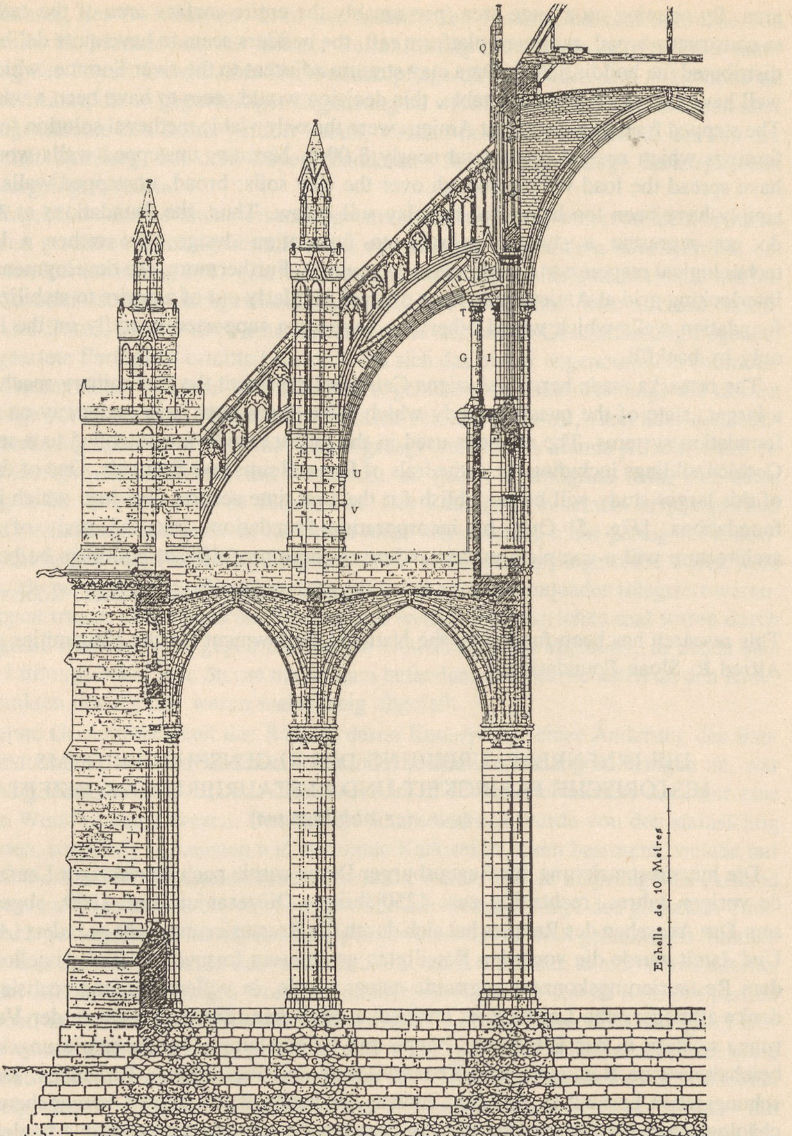

Fig. 5 Amiens Cathedral. Section of the choir including foundations. This section is pastiche created from two separate section drawings originally published by Durand.

area. By opening up a huge area (presumably the entire surface area of the cathedral) to construct a broad, mortared platform raft, the builders seem to have quite deliberately distributed the building load. On a clay stratum adjacent to the river Somme, which may well have meant a high water table, this decision would seem to have been a wise one. The stepped foundation walls at Amiens were the only viable medieval solution for stone footings which needed to descend nearly 8.00m. Narrow, unstepped walls would not have spread the load widely enough over the clay soils; broad, unstepped walls would simply have been too heavy for the clay soil below. Thus, the foundations at Amiens do not represent a stylistic solution to foundation design, but rather a logical, technological response to a particular site geology. Furthermore, the development of the interlocking grid at Amiens may have evolved similarly out of a desire to stabilize large foundation walls which would otherwise have been supported laterally on the interior only by backfill.

The remarks made here on Amiens Cathedral represent the preliminary results from a larger, state of the question study which the authors now have underway on Gothic foundation systems. The methods used in the present study are extended to a series of Gothic buildings including the cathedrals of Paris, Reims and Beauvais. One of the aims of this larger study will be to publish for the first time section drawings which include foundations. [*Fig. 5*] Only by incorporating foundations into the study of Gothic architecture will a complete understanding of these magnificant buildings be possible.

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DIE INNENRESTAURIERUNG DES REGENSBURGER DOMS: HISTORISCHE FARBIGKEIT UND RESTAURIERUNGSKONZEPT

(mit vier Abbildungen)

Die Innenrestaurierung des Regensburger Doms wurde nach vierjähriger Laufzeit Ende vorigen Jahres, rechtzeitig zum 1250jährigen Diözesanjubiläum 1989, abgeschlossen. Das Aussehen des Raumes hat sich durch die Restaurierung nicht geändert (*Abb. 2*). Und damit wurde die von allen Beteiligten gemeinsam formulierte Zielvorstellung, die dem Restaurierungskonzept zugrunde gelegt wurde, in vollem Umfang realisiert. Die denkmalpflegerische Leistung ist unsichtbar geblieben. Sie liegt nicht in der Veränderung, sondern in der Erhaltung, Pflege und Erforschung. Das Restaurierungskonzept beinhaltete eine Reinigung und Konservierung des überlieferten Bestandes. Die Forschungsarbeit bestand in den dem Einbau der neuen Bischofsgruft vorangehenden archäologischen Grabungen und der die gesamte Restaurierungsmaßnahme begleitenden Bauforschung und Befunduntersuchung. Die Grabungen wurden von S. Codreanu-Windauer vom Bayer. Landesamt für Denkmalpflege und K. Schnieringer geleitet. Die Bauforschung wurde im Rahmen eines von der Universität Bamberg (A. Hubel) beantragten Projekts der Deutschen Forschungsgemeinschaft von M. Schuller betreut. Die