Buried Structures

Static and Dynamic Strength

P. S. BULSON

B[redacted] Structures

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P. S. BULSON
Deputy Chief Scientific Officer,
Ministry of Defence and
Visiting Professor of Civil Engineering,
University of Southampton

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EDITOR'S FOREWORD

Dramatic innovations and developments have occurred in civil and structural engineering in recent years. Difficulties of analysis which appeared insurmountable only twenty years ago have largely disappeared with the advent of the mainframe computer and the finite elements method; new generation microcomputers now increasingly provide such analyses with great convenience and economy. The engineer today has more time to devise new forms of construction, to improve design details, and to allow for phenomena and data which were previously overlooked or approximated. Much of this new expertise has been used to improve the design of ships and aircraft, offshore platforms, subway systems, high-rise towers and buildings, and many other forms of construction previously designed by rules-of-thumb and simple codes of practice. There is now much more internationalism in engineering too, with design methods and codes becoming more standardized, and large computers providing technical literature and patent information from all over the world. There is a need for these advances to be presented to an international audience by leading engineers of international repute; this is the purpose of the new Civil Engineering Series by Chapman and Hall.

The third of the new series is by Dr P.S. Bulson who is head of a defence research establishment specializing in military engineering at Christchurch, England, and a visiting professor in the Civil Engineering department of Southampton University. He has worked for the British Ministry of Defence since 1953, following postgraduate studies at the University of Bristol and service as an officer in the Royal Engineers. Though interested in all aspects of military engineering, he has personally specialized in structural stability, pneumatic structures and underground structures. He is the author of many technical reports and papers, and has already written books entitled *Stability of Flat Plates* and (as co-author) *Background to Buckling*. He has contributed to other books on structural stability.

Dr Bulson's new book is entitled *Buried Structures: Static and Dynamic Strength*, which covers underground structures constructed by a 'cut and fill' method rather than by tunnelling. Though most of the research area is directed towards the optimum design of defence installations, pipelines and domestic nuclear shelters, similar conclusions and recommendations apply to buried structures constructed for any purpose. The book will therefore be of considerable interest to most civil and structural engineers, particularly those designing covered tunnels, conduits and defence works under static and dynamic loads.

E. Lightfoot
Oxford

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Preface

As a schoolboy I frequently journeyed to the Dorset coast through the road tunnel at Beaminster, built by Lang in the 1830s. Later, when I first became a student of engineering, the walk to lectures took me through the derelict surface workings of the great Dolcoath tin mine near Camborne in Cornwall. It never entered my mind that I would one day write on the subject of underground structures.

I became involved in the subject through a defence interest in the behaviour of thin-walled buried structures under static and dynamic surface loading, a subject not closely connected with the design of masonry tunnels or mine workings, but nevertheless relevant to the general field of soil–structure interaction. Recently I have detected an increasing civil engineering interest in the problem, and I have therefore attempted to summarize the available analysis and test work for the benefit of engineers and scientists coming to the subject for the first time.

I have acknowledged sources of information where they appear in the text, and I am indebted to the U.S. Army Standardization Office in London, and the U.S. Defence Nuclear Agency in Washington, for their help in obtaining clearance to quote from U.S. Technical Reports. There are inevitable gaps in the presentation because a good deal of information from defence research sources still carries a security classification and cannot be published in open literature. Because some of the experimental work was carried out before the days of metrication, readers are asked to accept a mixture of f.p.s. and SI units in the text. However, a conversion table is provided at the end of the Notation section on p. xvi.

I wish to record my thanks to Miss Joyce Carter, who typed the manuscript, and to Mr Phillip Read of Chapman and Hall, who waited so patiently for the final draft. Above all, I express my gratitude to Mr J. Ellis, former director of the Military Vehicles and Engineering Establishment, Ministry of Defence, for allowing me the facilities to complete the work, and for his encouragement.

P.S. Bulson
Christchurch, 1984

Notation

All symbols are defined in the text where they first occur. The symbols listed below are those that appear repeatedly, or are of greatest interest.

Lower-case letters

a	distance between circular holes
	vertical semi-axis of elliptic arch
	radius of cylindrical surface
b	width of underground structure
	horizontal semi-axis of elliptic arch
c	cohesion of soil
d	diameter
	displacement
d_c	diametrical shortening
f	stress
f_c	design stress, ultimate compressive strength
f_y	yield or proof stress
h	minor axis of ellipse
	equivalent wall thickness
k	soil constant
	modulus of passive resistance
	coefficient of subgrade reaction
k_0	coefficient of earth pressure at rest
k_c	constant of soil reaction for clay
k_L	coefficient of elastic soil reaction
k_m	modulus of soil reaction
	coefficient of soil reaction
	modulus of subgrade reaction
k_{m1}, k_{m2}	moment coefficients
k_{p1}, k_{p2}, k_{p3}	axial force coefficients
k_r	ratio between horizontal and vertical earth pressure
k_s	constant of soil reaction for sand
k_z	spring constant for soil

l	length of underground structure
n	volume of voids per unit volume of soil
	percentage void content
p	pressure
p_0	internal pressure
	atmospheric pressure
	static collapse pressure
p_1, p_2	uniform radial pressure
p_a	allowable surface pressure
	collapse pressure in air
p_{cr}	elastic critical radial pressure
p_{ex}	external pressure
p_i	interface pressure
	peak incident pressure
p_{max}	value of p_s at deep covers
p_r	peak reflected pressure
p_s	surface pressure to cause collapse
p_t	peak instantaneous transverse pressure
p_v	free field pressure
	free field stress
q	overpressure
r	polar coordinate
	distance from centre of circle
r_0	radius
r_p	projection ratio
r_{sd}	settlement ratio
r_u	ultimate unit resistance
s	shearing resistance of soil
s_x, s_y, s_z	remote state of stress
t	thickness
	time
	distance of water table above crown
t_0	duration of positive phase
u	pore pressure
	dilational seismic velocity
	radial displacement
v	tangential displacement
	impulse velocity
	velocity of shock front
w	weight of explosive charge
	radial deflection
$x, y, z,$	coordinate axes

Capital letters

A	arching factor
	footing area
	thrust area per unit length
A_g	geometry factor
A_S	plan area
B	width of underground structure
B_c	overall conduit width
B_d	ditch width
C_c	load coefficient (positive projection)
C_d	load coefficient (narrow trench)
D	diameter of underground structure
D'	flexural rigidity of pipe wall
D_c	diameter shortening
E	modulus of elasticity
E'	specific stiffness
E^*	modulus of equivalent pipe
E_c	elastic modulus of clay
E_s	elastic modulus of sand
	elastic modulus of soil
F	blast load
	concentrated load
	line load
G	shear modulus
G_s	secant shear modulus
H	depth of cover
$\bar{H}$	total impulse
I	second moment of area
	impulse
I_0	impulse to produce given level of damage
L	side depth of underground structure
	span
	path length of projectile
L_k	relative stiffness
M	bending moment
M_L	loading modulus of soil
ΔM_L	additional moment
M_P	ultimate moment (midspan)
M_S	secant modulus of soil
M_T	average tangent modulus for soil
M_U	ultimate moment (support)
	unloading modulus of soil

N	thrust in tunnel lining
N_f	flexibility number
P	vertical penetration
	force
R	radius
	stiffness–geometry factor
	rise of pipe arch
	angular linear penetration
R_B	moment reduction factor
R_S	stiffness of elastic medium
S	span of arch
	settlement
	perimeter of structure
T	periodic time
U	strain energy
W	yield of explosion
	concentrated surface load
	total weight of bomb
W_c	vertical load per unit length
W_e	equivalent weight
ΔX	horizontal deflection
ΔY	vertical deflection

Greek letters

α	semi-angle of arch
	semi-angle of bedding
	peak stress attenuation factor
	depth coefficient
β	soil–structure interaction factor
	angle between vector and vertical
β'	burial factor
γ	soil density
	partial safety factor
$\gamma_1, \gamma_2, \gamma_3$	partial safety factors
γ_B	bedding factor
γ_d	drained density
γ_h	hyperbolic shear strain
γ_s	saturated density
γ_T	deflection/time factor
γ_w	density of water
δ	deflection
δ_1, δ_2	central deflections

ε_s	lateral strain in soil
$\varepsilon_\mathrm{x}, \varepsilon_\mathrm{y}$	direct strain
ε_hL	hardening strain of backpacking
η	safety factor
θ	angle of obliquity
λ	coefficient of ground reaction
μ	ductility ratio
ν	Poisson's ratio
ν_s	Poisson's ratio for soil
ρ	mass density
	radius of curvature
σ	breaching range
	stress
σ_c	ring compressive stress
	tangential compressive stress
	compressive stress to cause collapse
	ultimate strength
σ_cr	critical elastic buckling stress
σ_I	largest principal stress
σ_l	longitudinal stress
σ_p	compressive yield stress
σ_r	radial stress
σ_u	ultimate soil bearing strength
σ_v	vertical soil stress
σ_vh	hydrostatic stress
σ_x	stress in x-direction
σ_y	overburden pressure
σ_θ	tangential stress
$(\sigma_\theta)_R$	tangential compressive stress
$\tau_{r\theta}$	shear stress (polar coordinates)
τ_{xy}	shear stress (cartesian coordinates)
ϕ	angle of shearing resistance
ω	angular velocity

Conversion factors

Property	SI Units	f.p.s. Units
Length	1.0 mm	0.0394 in.
	1.0 m	3.28 ft
Area	1.0 mm^2	0.00155 in.^{2}
	1.0 m^2	10.76 ft^2
Mass	1.0 kg	2.205 lb
Density	1.0 kg m^{-3}	0.0624 lb ft^{-3}
Force	1.0 N	0.225 lb f
	1.0 kN	225 lb f
Stress	1.0 kN m^{-2}	0.145 lb in.$^{-2}$
	15.44 N mm^{-2}	1.0 tonf in.$^{-2}$

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CHAPTER ONE

Introduction

1.1 Early history

For many thousands of years, the main subterranean activities of man were cave dwelling, mining and tunnelling. Mining was often carried out at considerable depths in ancient rocks, and the cavities excavated for this purpose were generally stable, with some form of structural lining being used as a means of preventing local falls of the roof or sides. Many mining galleries could be left unlined, just as the galleries of burrowing animals are unlined, and many only needed local roof props.

Tunnelling, on the other hand, was often carried out at shallow depths in younger geological formations, and was used for water supply, drainage or military fortifications. The lining was needed to maintain the integrity of the cavity for conveyance purposes, and was designed as a permanent structure, resisting local loads by using brick or masonry in the form of vaulted arches. The tunnels of Babylon, Athens and Rome were built in this way, and there were few design changes throughout ancient history. Even in the Middle Ages, the substructures of our cathedrals and castles made extensive use of the masonry vault.

Between the seventeenth and nineteenth centuries, there were notable advances in the techniques of tunnelling, owing to the introduction of gunpowder and dynamite for blasting, and of hydraulic and pneumatic drills for rapid excavation. These advances coincided with a sharp increase in the need for traffic tunnels (highway, railway, navigation and subway) and conveyance tunnels (water supply, drainage, sewage, hydroelectricity), particularly in Europe. Tunnels were normally constructed without disturbing the surface, using what became known as 'classical' methods, where temporary timber elements in a variety of configurations were employed to support the heavy linings during erection. Later, Brunel invented the shield method, a moving metal casing driven in advance, to support the surrounding earth or rock without the need for timbers.

Lining materials changed from brick and masonry to concrete, reinforced concrete, cast iron and steel, particularly in the construction of highway and subway tunnels in the early part of this century. Many shallow-depth 'metro' tunnels were constructed by the 'cut-and-cover' method, particularly if the soil was poor and saturated by ground water. There was a need for all these structures to withstand the long-term degeneracy associated with a soil and water environment, uneven bedding and fluctuating loads. They were therefore rigid in construction, inherently strong and robust. Modes of failure were similar to those exhibited by masonry arches – the formation of hinges at the springings and crown of the arch or vault, or inward failure of the lower sides due to lateral pressure followed by upward collapse of the floor. Structural analysis supporting the design was mainly concerned with establishing levels of loading and predicting failure of the heavy cross sections. Many designers still employed thrust line theory to check the stability of the lining in the way it was used in the seventeenth century to design domes and vaults.

1.2 Contemporary structures

At the end of the nineteenth century, mass-produced corrugated steel sheeting became available to world markets, and its use in all fields of the construction industry grew rapidly. Corrugated metal pipe was soon developed and used for culverts; it was shop fabricated into a variety of cross-sectional shapes (round, elliptic, pipe arch and underpass), and as experience grew diameters were increased to 2.5 m and above. This was probably the first use of thin-walled flexible linings for subterranean structures, and gave rise to a good deal of laboratory and field research in the early part of this century towards a rational design method. The idea of using soil–structure interaction as a means of supporting the loads on flexible pipes and tunnels began to be formulated as a result of this research.

Heavier plating was developed, with larger corrugations, capable of field assembly into culvert and underpass shapes, and diameters of over 6 m were successfully constructed. It was soon clear, however, that in addition to the problems associated with elastic deflections, and the mobilization of the resistance of the surrounding soil, there could be a danger of instability under compressive forces of the relatively thin walls of these structures – a condition that had not been met in classical tunnel design. Research on this aspect was sponsored in the USA by the American Iron and Steel Institute in the late 1960s.

Meanwhile, during the Second World War, it became necessary to design underground shelters as a protection against blast effects from high explosives, for both civil and military purposes. The economic thin-walled lining was used extensively in corrugated or stiffened form, and considerable knowledge was accumulated on the behaviour of this type of structure under dynamic loading. After the war, the military use was extended to take account of the blast effects of nuclear devices on subterranean military installations of varying types, and more research was undertaken. The loading differed from that associated with culverts and underpasses, in that the pressure due to the soil cover was augmented by a surface blast pressure, dynamic in character. The setting of some of the structures was no longer horizontal – some thin-walled tubular constructions were set vertically to act as subterranean missile-firing silos.

1.3 The future

At the time of writing, even larger buried culverts are being used, particularly in North America, and some have been instrumented to study their performance. Arch-shaped culverts with spans greater than 15 m have been the subject of field experiments to measure soil arching, displacement and deformation, and earth pressures in adjoining areas. Cover depths of more than 13 m have been employed.

The large-diameter flexible pipe is also required for the development of Britain's water resources, particularly for the proposed inter-regional grid to transfer bulk water supplies quickly between major strategic centres. In a survey of the problem, particular attention has been given to the analysis of reinforced and unreinforced plastic pipes with diameters up to 5 m, including the placing and compaction of the backfill.

In the future, one foresees increasing interest in the design and construction of structures under the sea bed, in conjunction with deep-sea mining and energy exploration. The loading on a structure is then a large hydrostatic pressure due to the depth of water, superimposed on that due to a relatively shallow covering of sea-bed material – a problem not unlike that of the blast-resistant buried structure. Few codes of practice are likely to exist, so it is important that designers have a good understanding of the fundamental behaviour, with particular regard to stability, limit states of deflection and deformation, and safety.

The distinction between rigid and flexible structures may also become less obvious as time goes by. Taking underground pipes as an example, a rigid pipe of concrete or cast iron will normally fail by bending of the wall, and a flexible pipe (plastic, corrugated or sheet steel) by buckling. But the distinction is not an ideal one because most structures have some degree of flexibility, and for unconventional designs it may be better to consider the whole range of behaviour in terms of slenderness, rather as we do for struts, plates and shells. Further, unlike many above-ground structures, the modes of failure are influenced by the properties of the surrounding soil, and the loading is influenced by deformation in a non-linear fashion. The nature of the backfill is also important for structures emplaced by the cut-and-cover method.