OVERFILLED PRECAST CONCRETE ARCH BRIDGE STRUCTURES

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ABSTRACT

For many centuries, the arch has been used as a safe, durable, economical and aesthetic structural form, perfectly suited for the construction of short span bridges. Overfilled precast concrete arch bridge structures have many advantages over other bridge systems for span ranges of up to 100 feet.

INTRODUCTION

Countless bridges have been erected over the centuries throughout the world. The vast majority of these bridges were and are of unspectacular short spans of less than a hundred feet. Nevertheless, they fulfill their intended purpose just as well as any spectacularly designed and record-breaking suspension bridge.

Overfilled precast concrete arch bridge structures using soil-structure-interaction to achieve stability and strength fulfill a key segment of today's bridging requirements. They have many advantages over other bridge systems for this short-span range.

BRIEF HISTORY OF ARCH BRIDGES

For several millennia, the arch has been recognized as a safe, durable, economical and aesthetic structural form, perfectly suited for the construction of short span bridges or long bridges and viaducts using multiple spans.

Arches were used as early as 3000 B.C. by the Ancient Egyptians. Roman engineers used the semi-circular stone arch so extensively that the design is still referred to as the "Roman Arch". Usually the spans of these ancient structures ranged to about 90 feet. Until the 18th century, almost all stone bridges were of this design. Geometric and hydraulic considerations generally resulted in segmental arches (circular arches of less than 180 degrees). Still later, other geometric forms such as the ellipse and parabola were also successfully applied. Since the late 19th century, the mathematical analysis of arches has usually resulted in an arch ring of varying thickness even after reinforced concrete became a common construction material.

In early bridge building, masonry arches were erected to impressive size, limited only by the physical properties of the construction material. Among the most daring of these masonry arch structures is one built by I.K. Brunel in 1838, the Maidenhead Bridge across the Thames River. The railway bridge, still in use today, has two spans of 128 feet and a rise of 24 feet only.
Another impressive masonry arch, the Union Arch Bridge, was erected in North America near Washington, D.C. during the American Civil War. The structure, also still in use, has a single span of 220 feet with a rise of 57 feet.

Early concrete arches copied their masonry forerunners and were therefore hingeless. Later, the concepts of one, two and three hinges were applied. By the 20th century, even reinforced concrete arches were given elaborate hinges. For bridges, the 2-hinge version was the most popular.

In the 20th century, the process of precasting structural elements developed, with blocks, lintels and pipes being among the first items to be produced in this way. As highways and materials handling equipment improved, larger precast elements became feasible. Since the 1950's, it has become routine for multi-ton members to be built and transported over long distances from casting plants to project sites. Segmental bridge construction, developed in post-World War II Europe, has gained wide usage and has produced many impressive structures through the use of multi-ton precast construction units.

OVERFILLED ARCH ANALYSIS
BACKGROUND

For an overfilled arch structure, the fill represents more than a loading. Through its passive resistance, it also contributes to the load carrying capacity of the arch and thus becomes a structural part. This phenomenon is commonly known as soil-structure-interaction.

The design of slender overfilled concrete arch structures was investigated extensively in the early 1960's by Swiss engineer Werner Heierli in connection with the construction of the Swiss Federal highway system. Clearance requirements for underpasses were often identical, and a pre-engineered precast concrete arch system presented an economical solution for the construction of such underpasses.

Heierli’s design approach made wide use of soil-structure-interaction. In order to verify the results of his theoretical investigations, a first full-scale test was performed in 1965/1966 in a gravel pit near Zurich, Switzerland. The test structure consisted of curved precast concrete elements with a cast-in-place butt joint at the crown. The arch had a span of 46 feet and a rise of 16 feet. The wall thickness was 6 ½ inches only.

Vertical and horizontal deflections were measured throughout the arch structure during backfill operation and under moving live loads and heavy static loads. The arch deformations were used to determine the lateral earth pressures for the different loading cases and to evaluate the soil-structure-interaction behavior.

As a result of the successful experiment, the first so-called “BEBO™ System” bridge was built in 1967 on Swiss Federal Highway Number 1. The bridge has remained in service with a virtually maintenance-free history to date.

With the introduction of the precast arch system in Germany, a second full scale test was performed in 1973 under the supervision of the German Government's Institute for Road Research. This test arch was constructed of flat plate elements connected with cast-in-place joints and had a span of 40 feet and a rise of 10 feet. The wall thickness here was 8 ½ inches. Apart from deformation gages, special earth pressure cells were used to measure the following:

- Backfill resistance resulting from arch deformation
- Bearing behavior under loads exceeding maximum service loads
- Influence of the compaction density of backfill
- Behavior under asymmetrical backfill conditions
- Load distribution under concentrated loads
The soil-structure-interaction was investigated under conditions which included variations in overfill depths, degree of backfill compaction and the angle of internal friction of the backfill material.

The relation between arch deflection and change of earth pressure coefficient could be derived from the test results, and has since served as a basis for the BEBO™ design method for overfilled concrete arches. Besides its main application for the development of a precast concrete arch bridge system, the design concept has also been extensively used for the analysis of cast-in-place cut-and-cover tunnels and other underground facilities.

Further research programs have been performed with overfilled concrete arch structures through the years, among them one by the University of Adelaide's Department of Civil Engineering, and the latest, by the University of Massachusetts; all confirming the validity of the BEBO™ arch analysis approach and demonstrating the large load carrying capacity reserves inherent in the overfilled arch concept.

THE PRECAST ARCH BRIDGE SYSTEM

The original BEBO™ System arches were polygonal, built from flat plate elements, connected on site with welded, and later cast-in-place, joints. Scaffolding was needed to initially support the plate elements.

Most of the BEBO™ System structures built in Europe until the end of the 1970's are of this polygonal plate type. Using specially shaped plate elements, the entrances to the arch structures could be formed without the need for extra wing walls or spandrel walls.

In 1979, a refined arch system was introduced in the United States in cooperation with American engineer Neal FitzSimons of Kensington, Maryland. In order to reduce on-site labor, the plate system with its elaborate joints was abandoned for a system using curved arch elements. Spans were bridged now with one single element, a"single-leaf", or for larger spans with two "twin-leaf" elements, connected with a cast-in-place crown joint. Scaffoldings were no longer necessary, and the installation time was drastically reduced.

The arch end areas were also treated differently. Now, spandrel and wing walls were used to form the entrances of the arch structures.
Foundations for the arch system structures most often are cast-in-place spread footings. These are normally slabs, or slabs with a pedestal, depending on the depth of bearing. The footings have "keys" (shallow troughs) into which the arch elements are placed. The keys are then grouted. Statically, the performance of that arch/footing connection is assumed to be that of a hinge. Experience shows that the overfilled arch exhibits practically no rotation at the hinges.

Soil conditions may preclude the use of spread footings. In these cases, piles, inverted arches or flat slabs can be used.

The arch system was continuously extended and currently comes in a series of standard pre-engineered profiles with spans from 12 to 84 feet. Each arch size or type includes a number of subtypes with different rises.

Overfilled Arches:
- use less materials (up front savings)
- offer superior stability and structural safety
- have a continuous joint-less pavement on top (no costly bridge deck or transition joint repairs)
- are well protected from environmental impact and deicing agents
- cushion the effects of live load impact
- are durable and exhibit very low life cycle costs
- have low sensitivity to differential settlement (both in transverse and longitudinal direction)
- minimize the road icing hazard
- are aesthetically pleasing and blend well with natural surroundings
- allow rivers to keep their natural bed under the bridge

If constructed from precast elements, overfilled arches:
- are quickly installed, taking weeks off construction and annoying road closings
- minimize disruption of streambeds during construction
- allow temporary installations

OUTSTANDING INSTALLATIONS

A number of outstanding BEBO™ Bridges have been built through the years, among them:

**Hope Island Golf Club Bridge**, Queensland, Australia, built 1991. The 40/60/40 feet span bridge has been given a special architectural spandrel wall finish.
**PM Garden Bridge, Putrajaya, Malaysia**, built 1998. The 84 feet center span holds the current span record for overfilled precast concrete arch bridges.

**Putrajaya R3 Bridge, Malaysia**, built 1998. 660 twin-leaf arch elements of 18 tons were needed for this 15-cell multispan bridge.

**Metroplex, Montgomery, PA, U.S.A.**, built 1999. The arch with a span of 30 feet is over 1500 feet long.

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**CONCLUSIONS**

For many centuries, the arch has been used as a safe, durable, economical and aesthetic structural form. Using modern construction materials and analysis tools, and taking advantage of the supportive action of compacted backfill, the ancient arch could be refined into a slender structure that can be prefabricated at a central plant and transported to the site for installation.

Precast concrete components, manufactured under controlled conditions, reach a very high degree of strength and durability, and structures built from such components generally require very little maintenance. A major strong point of overfilled precast concrete arch bridge structures therefore is that they are designed and built to last. They withstand both the elements and time.

The continuity of the pavement over the bridge highly contributes to the low life cycle costs of overfilled arch bridges, avoiding annoying road closings for bridge deck and transition joints maintenance work.

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