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Comparison of the seismic response of reinforced auger pressure grout and concrete columns

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ABSTRACT

Despite the wide use of grout as a structural material due to easy construction and cost-effectiveness, its seismic performance has rarely been evaluated experimentally. In particular, reinforced grout columns which may experience significant lateral deformation need experimental evidence to validate their adequacy. This paper summarizes findings from a relevant experimental study, which consists of five cyclic tests and one hybrid simulation test conducted at the University of California, Berkeley. The results show that reinforced auger pressure grout columns under cyclic lateral load and high constant axial load can provide ductile and reliable behavior in flexure, comparable to that of similarly configured reinforced concrete (RC) columns. Therefore, these reinforced grout columns can be considered as an adequate alternative to RC columns subjected to medium to high compressive axial loads in regions of high seismicity.

1. Introduction

Grout (i.e., concrete without coarse aggregate) has been historically used for the construction of various structures, but it was not considered as a suitable material for load-bearing members. However, after it was first introduced in the 1940s, piles made of auger pressure grout (APG), whose construction technique is also known by a variety of names including auger cast piles, continuous flight auger (CFA) piles, and auger cast-in-place (ACIP) piles, have been widely accepted as an alternative to conventional reinforced concrete (RC) piles [1]. APG piles are constructed with reinforced grout as opposed to conventional RC piles. This construction technique results in speedy installation and reduced construction cost, which can offset higher initial material cost.

As various design codes state, the difference between grout and concrete is the existence of coarse aggregate in the mix. ACI 318-11 [2] defines concrete as containing cement, water, fine aggregate, coarse aggregate, and admixtures. Therefore, the mix without coarse aggregate is viewed differently. According to ACI Committee E-701 [3], "aggregate is granular material such as sand, gravel, crushed stone, blast-furnace slag, and lightweight aggregates that usually occupies approximately 60–75% of the volume of concrete, and the properties significantly affect the workability of plastic concrete and also the durability, strength, thermal properties, and density of hardened concrete." Since grout enhances workability, it represents an attractive alternative to concrete. However, it may cause deterioration in durability and strength, because most aggregates are several times stronger than the other components in the concrete mix. In addition, problems may result from creep and shrinkage in the grout. Due to the higher ratio of cement, the effect of shrinkage and creep is more significant than that in concrete. Higher hydration heat is another problem, and it may cause more severe cracks in grout than in concrete.

Significant amount of research has been devoted to the evaluation of the static capacity of APG systems as discussed in [4–11]. These research efforts confirmed the reliability of the APG piles under various soil conditions. In addition, appropriate design methods of APG piles and fairly accurate estimates of their axial capacity were also provided. However, some questions have been raised about the behavior of reinforced grout members, particularly in shear and bending. The questions pertain primarily to the decreased amount of available aggregate interlocking in the grout and the degree of adhesion of the grout to the reinforcing bars.

Reinforced grout columns are not commonly used in buildings and bridges. However, because of the speedy installation and reduced construction cost, APG systems have the potential to be used in columns in addition to piles, e.g., for purposes of accelerated bridge construction (ABC). To examine the seismic

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performance of reinforced grout columns as appropriate load-bearing members, an experimental study was conducted at the University of California, Berkeley.

In this paper, the effectiveness of APG columns is examined by comparing their performance to that of RC columns through five cyclic tests. Due to the application of large lateral displacements and axial load ratios representative of bridge columns, the test results are relevant to examine the behavior of bridge columns in high risk seismic zones. For comparison, an APG column having transverse reinforcement with smaller spacing was included in the test matrix. In addition, a hybrid simulation (HS) test was conducted to evaluate the behavior under the effect of more realistic seismic loading due to an earthquake ground motion and to compare the responses of test specimens under different loading conditions.

2. Design of experimental program

The test approach, matrix, and setup are presented in this section. The test setup was designed to be flexible enough to allow a major parameter to be varied, namely the effect of axial load on the test specimen. In that regard, the test matrix included specimens subjected to no axial load and others subjected to large axial load (300 kip (1334.5 kN)) corresponding to $0.16A_gf'_c$ of APG specimens, and $0.20A_gf'_c$ of RC specimens, where A_g is the column gross cross-sectional area and f'_c is the 28-day compressive strength of the column material, i.e., grout or concrete. The adopted upper bound axial load ratios, i.e., 16% and 20% of $A_gf'_c$ for APG and RC columns, respectively, are in the high axial load ratio range that RC columns of a common bridge would experience under the combined effect of gravity loads, axial forces due to the vertical component of a ground motion, and those due to the overturning moments resulting from the horizontal component of a ground motion. Moreover, these axial load ratios result in a relatively high bending moment capacity, considering the P–M interaction of each section. It is noted that the HS test, as explained later, is conducted without axial load, which results in a conservative moment capacity, yet unconservative ductility as compared to the case with axial load.

2.1. Test approach

2.1.1. Cyclic tests (SP1–SP5)

The adopted approach to resolve the question of the seismic adequacy of reinforced grout columns was to perform large-scale cyclic lateral load tests. The tests were performed on circular RC and reinforced APG column specimens, free at the loaded top and supported on stiff reaction mats at the bottom, which are designed to remain elastic and un-cracked. The specimens are considered as 1/5 scaled versions of the columns of the Plumas-Arboga overhead bridge located in Northern California. Detailed information on the geometrical and material properties of the test specimens is presented later. Specimens were tested by imposing a constant axial load and loading the specimen laterally with a cyclic displacement regime. The cyclic displacement protocol incorporated three reversed cycles at each level of maximum cyclic displacement, namely $0.5\Delta_y$, $1.0\Delta_y$, $2.0\Delta_y$, $4.0\Delta_y$, etc., until specimen failure. The displacement corresponding to the onset of longitudinal bar yielding, Δ_y, was determined from prior analysis as 0.570 in. (14.5 mm) for the specimens without axial load and 0.670 in. (17.0 mm) for the specimens with 300 kip (1334.5 kN) axial load. During testing of SP1 and SP3, the estimated yield displacement was revised based on approximate comparison of reinforcing steel strain measured at four sections with gages near the base (i.e., 0.0–0.75D above the base) of the specimen in the first two groups of cycles (i.e., the $0.5\Delta_y$ and $1.0\Delta_y$ groups) with the actual material yield values obtained from testing steel coupons. The revised values used starting from the $2.0\Delta_y$ group, were 0.655 in. (16.6 mm) and 0.770 in. (19.6 mm) for the specimens without and with 300 kip (1334.5 kN) axial load, respectively. Table 1 summarizes the applied displacement histories.

Table 1
Loading program.

Group	Specimens without axial load [in.] ([mm])	Specimens with axial load [in.] ([mm])	Loading rate [in./s] ([mm/s])
$0.5\Delta_y$	0.285 (7.24)	0.335 (8.51)	0.01 (0.25)
$1.0\Delta_y$	0.570 (14.48)	0.670 (17.02)	0.01 (0.25)
$2.0\Delta_y$	1.310 (33.27)	1.540 (39.12)	0.01 (0.25)
$4.0\Delta_y$	2.620 (66.55)	3.080 (78.23)	0.01 (0.25)
$6.0\Delta_y$	3.930 (99.82)	4.620 (117.35)	0.02 (0.51)
$8.0\Delta_y$	5.240 (133.10)	6.160 (156.46)	0.02 (0.51)
$10.0\Delta_y$	6.550 (166.37)	–	0.05 (1.27)
$12.0\Delta_y$	7.860 (199.64)	–	0.05 (1.27)

2.1.2. Hybrid simulation (SP6)

Specimen SP6 was tested using HS, a test method to examine the seismic response of structures using a hybrid model comprised of both physical (experimental) and numerical (analytical) substructures. The method consists of solving the governing equations of motion of this hybrid model under external dynamic excitation, most commonly due to a ground motion, using numerical integration. The test specimen, i.e., the experimental substructure, is included in the solution by imposing the computed displacements, measuring the corresponding forces and using these forces in the computations to advance the numerical integration. Combining realistic dynamic excitation in shaking table tests, which are expensive and/or restrictive for the specimen sizes, with the ability to test large-scale structures in the simpler quasi-static testing, HS came forward in recent years as a cost-effective alternative for structural testing. A summary of the literature on various aspects of HS is given in [12].

Unlike a shaking table test [13], the HS method allows the investigation of the response of a structure under a ground motion without the need to physically include the required mass assembly. Accordingly, HS can be conducted on a quasi-static test setup. Therefore, testing SP6 using HS was a useful and efficient addition to the test program for assessing the seismic response of the APG columns without any additional modifications on the test setup used for the first five test specimens. Furthermore, the HS of SP6 demonstrated a recently developed HS system at the Structures Lab., Dept. of Civil and Environmental Engineering, University of California, Berkeley. The HS system consists of a controller, a data acquisition (DAQ) system, a digital signal processor used as the computational platform and the test specimen, Fig. 1. The details of this system, enhanced with real-time HS (RTHS) capabilities, can be found in [14].

The hybrid model, presented in Fig. 1, consists of the APG column specimen as the experimental substructure and a concentrated top mass and a dashpot with mass-proportional damping as the analytical substructure. The axial force was not applied in SP6 similar to SP1 and SP2, as discussed in the test matrix in the next section. In order to obtain representative period and strength/weight ratio, computational mass was chosen as 35.5 tons. The damping ratio was chosen as 5% of the critical, as identified by Lee and Mosalam [13] from shake table tests of bridge columns. The 196° component of the 1994 Northridge earthquake ground motion recorded at Canoga Park, Topanga Canyon station (RSN 959 in PEER NGA database [15]) was employed as the input ground motion excitation. This motion was applied in eight